Geovisual Analytics and the Science of Interaction: An Empirical Interaction Study

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ABSTRACT: Among the most pressing research and development challenges facing geovisual analytics is the establishment of a science of interaction to inform the design of visual interfaces to computational methods. The most promising work on interaction to date has attempted to identify and articulate the fundamental interaction primitives that define the complete design space for the user experience. In this paper, we take the logical next step beyond this prior research, reporting on a controlled interaction study to learn how variation in interaction primitive combinations impacts broader interaction strategies (i.e., to learn how interaction primitives relate for both design and use). *GeoVISTA CrimeViz*—a geovisual analytics application developed in partnership with the Harrisburg (Pennsylvania, USA) Bureau of Police—was leveraged as a living laboratory for examining the nature of interaction strategies as they are built from interaction primitives. Ten law enforcement officers with the Harrisburg Bureau of Police completed a set of fifteen benchmark tasks based on a three-stage interaction primitive taxonomy while their interactions were logged. Experimental results revealed several noteworthy characteristics of the relationship between interaction primitives and interaction strategies, including an increased reliance on the interface as the objective increases in sophistication and the effectiveness of, although at times over reliance upon, Shneiderman's visual information seeking mantra as an analytical strategy. Further, consistently successful and suboptimal interaction strategies were characterized in terms of their constituent interaction primitives and articulated as user personas, allowing for the establishment of interface design and use recommendations for circumventing negative personas.

KEYWORDS: geovisual analytics, science of interaction, interactive maps, UI/UX design, interaction primitives, interaction strategies, interaction personas

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****Figures and tables at end of document**

1. Introduction

Geovisual analytics at its core requires a synergistic relationship between humans and machines. Geovisual analytics differs from prior research approaches to cartography and visualization in its focus on the human reasoning faculties needed to build evidence and generate actionable knowledge about complex problems (Andrienko et al. 2007). However, the complexity of the problem at hand—and the datasets collected about said problem—too often surpass human cognitive limits. As a result, geovisual analytics also differs from prior research approaches in its application of sophisticated statistical and computational techniques to extract relevant insights from voluminous datasets (Chen et al. 2008). In this way, the machine scales the human to meet the complexity of the problem.

In the following, we treat neither the human nor the machine in isolation, but rather approach the 'glue' that makes their synergy possible: the visual interface. The design and development of map-based interfaces that are both useful and usable is tantamount to successful geovisual analytics, as it is through the interface that insights are shared between human and machine. Our research contributes to an emerging ***science of interaction*** that spans the related fields of human-computer interaction, information visualization, and usability engineering (Pike et al. 2009). Importantly, Thomas et al. (2005: 76) include "the creation of a new science of interaction to support visual analytics" among the core set of research and development initiatives facing visual analytics.

Existing research on interaction to date has attempted to describe the complete interaction solution space by reducing the interaction process into its smallest structural constituents, resulting in taxonomies of ***interaction primitives*** (Roth 2012). Such interaction primitives are the conceptual parallel to the visual variables in representation design (Bertin 1967|1983), and therefore serve as a foundational framework for the science of interaction. However, there is relatively minimal research leveraging the interaction primitives to track and assess competing ***interaction strategies***, or sequences of interaction primitives applied to complete an exploratory or analytical task (Edsall 2003). In this paper, we take the logical step beyond our past work to identify and articulate interaction primitives by investigating how variation in interaction primitive combinations impacts broader interaction strategies. By relating successful or suboptimal interaction strategies to their constituent interaction primitives, the ultimate promise of a science of interaction may be realized: empirically-derived and broadly-generalizable design and use guidelines for visual interfaces.

To this end, we conducted an interaction study with a geovisual analytics application called *GeoVISTA CrimeViz* using the interaction primitives presented in Roth (2013a) as the theoretical unpinning for evaluating user interaction strategies with the application. *GeoVISTA CrimeViz* (**Figure 1**) is a collaborative project between the Penn State GeoVISTA Center and the Harrisburg (Pennsylvania, USA) Bureau of Police. The *GeoVISTA CrimeViz* application enables law enforcement officers to build complex queries of their crime incident database in space, time, and attribute and to generate flexible aggregates of the query results for display in linked map and timeline visualizations. Following Shneiderman's (1996: 337) ***visual information seeking mantra*** of "overview first, zoom and filter, then details on demand," law enforcement officers ultimately can drill-down into potential incidents of interest, building evidence for solving past crimes and generating actionable knowledge for preventing future ones.

[Figure 1 approximately here]

This paper proceeds with four additional sections. In the next section, we review core concepts regarding the science of interaction and summarize existing interaction studies in cartography and geovisual analytics. In the third section, we describe the method design for the interaction study. Ten law enforcement officers at the Harrisburg Bureau of Police completed fifteen benchmark tasks using *GeoVISTA CrimeViz*, with the benchmark tasks informed by, and resulting interaction logs coded according to, our prior work on interaction primitives. The results of the interaction study are discussed in the fourth section and the concluding remarks are offered in the fifth and final section.

2. Background

Contemporary research on the science of interaction recognizes a fundamental distinction between ***interactions***, or the overarching action-response sequence between a human and a machine, and ***interfaces***, or the specific tools developed to support the interaction in a digital environment (Beaudouin-Lafon 2004). Professionally, it is increasingly common to refer to this distinction as ***user experience (UX)*** design versus ***user interface (UI)*** design (Hassenzahl and Tractinsky 2006). By considering the complete user experience, Norman (1988) segments a single interaction (physical or virtual) into a series of seven ***stages***: (1) forming the goal, (2) forming the intention, (3) specifying an action, (4) executing an action, (5) perceiving the state of the system, (6) interpreting the state of the system, and (7) evaluating the outcome. **Table 1** describes how an interaction with *GeoVISTA CrimeViz* may occur in these seven stages. To support the interaction, the interface must be designed to include ***visual affordances***, which help the user execute the action sequence (i.e., Stages #1-4), as well as ***visual feedback***, which help the user evaluate the system response (i.e., Stages #5-7). In this way, the interface supports a synergistic relationship between the human and the machine, with the human modifying the visuals processed and displayed by the machine and the machine modifying the human's reasoning process (Roth 2013b).

[Table 1 approximately here]

Theoretically, a unique taxonomy of interaction primitives can be assembled at each of Norman's (1988) stages of interaction in order to articulate, and ultimately to account for, the complete UX design space. In past work, we found that most existing taxonomies of interaction primitives align primarily with one of three of these stages (Roth 2012; MacEachren 2013). First, many taxonomies enumerate user ***objectives***, or close-ended tasks that can be completed with a visualization. Objective taxonomies align closely with the second stage of interaction, forming the intention. Notably, Crampton (2002) argues that objective primitives increase incrementally in their ***level of sophistication***, or cognitive difficulty, with the *compare* objective comprising two simpler *identify* objectives, plus the cognitive comparison, the *rank* objective comprising a series of *compare* objectives, plus the cognitive ranking, and so on. A second approach is to compartmentalize primitives according to interface ***operators***, or the generic kinds of functionality that can be implemented in an interface. Operator taxonomies align closely with the third stage of interaction, specifying an action. The final approach lists primitives according to characteristics of the interaction ***operand***, or the recipient of the interaction. In geovisual analytics, the operand often is the map itself, or the object being manipulated between the fourth (executing an action) and fifth (perceiving the state of the system) stages of interaction. Importantly, objective and operand combinations describe ***benchmark tasks*** for geovisual analytics, as they define both the user's intention in manipulating the visualization and the aspect of the visualization to be manipulated.

Our research presented here builds upon a small set of interaction studies reported in the cartography and geovisual analytics literature, including MacEachren et al. (1998), Andrienko et al. (2002), Edsall (2003), and Robinson (2008a, 2008b); a systematic review of these studies can be found in Roth (2011). In an ***interaction study***, participants complete a set of benchmark tasks (as defined above) with a given interface in a controlled setting while their performance is captured in an ***interaction log***, or a listing of the interactions employed while responding to the each benchmark task along with a timestamp indicating when the interaction was performed (Robinson et al. 2005). For each of the aforementioned interaction studies, a purpose-driven interaction primitive taxonomy was developed to relate the interaction logs to the evaluated benchmark tasks. While such an ad hoc approach can reveal prototypically successful and suboptimal interaction strategies with a single interface, the lack of consistency in the purpose-driven taxonomies makes triangulation of insights across interaction studies—and generalizability of insights to all UI/UX design contexts—difficult.

To improve generalizability, and thus approach the science of interaction, we leveraged an empirically-derived, 'composite' interaction primitive taxonomy to inform the interaction study of *GeoVISTA CrimeViz*. Also in prior work, the first author completed a card sorting study requiring participants to organize example statements derived from both literature and practice on interactive cartography and geovisual analytics into logical categories (Roth 2013a). **Table 2** lists and defines the primitives included in the resulting 'composite' taxonomy, organized by objective, operator, and operand. As described below, we used the objective and operand dimensions to inform the benchmark tasks included in the interaction study, and used the operator dimension to inform coding of the interaction logs produced during the interaction study.

[Table 2 approximately here]

3. Methods

3.1 Participants

We purposively sampled ten participants from the Harrisburg Bureau of Police to participate in the interaction study using *GeoVISTA CrimeViz* as a 'living laboratory'. The primary criteria for participation in the interaction study included work responsibilities that would be supported by *GeoVISTA CrimeViz* once transitioned (i.e., participants were actual end users) and general familiarity with the *GeoVISTA CrimeViz* beta version (i.e., existing use of partially-featured versions made available to the Harrisburg Bureau of Police). The participant sample therefore was characterized by high levels of user expertise and motivation. The sample size of n=10 aligns with expert involvement in the interaction studies reviewed above, which ranges from n=6 to n=10 experts.

We administered a background survey prior to testing in order to establish several characteristics of the participants. Four participants had no post-secondary degrees (although all indicated that they had taken training courses through the Harrisburg Area Community College), two participants held an Associates degree, and four participants held a Bachelors degree; all Associates and Bachelors degrees were in Criminal Justice. All ten participants were sworn officers and thus were trained in law enforcement and policing. The majority (9 of 10) of participants reported making maps either yearly or rarely, with only one participant making maps daily. The majority (7 of 10) of participants reported using maps at least monthly, with half (5 of 10) using maps weekly or daily.

3.2 Materials and Procedure

We conducted the interaction study in a private room used for depositions and interrogations in the Harrisburg Police Headquarters. We configured a simple usability laboratory in the private room, which consisted of a laptop computer that we used during testing and an external monitor, keyboard, and mouse that the participant used during testing. We set the laptop and external monitor opposite each other on a central table in the room such that we were facing the participant during testing. A duplicate display of *GeoVISTA CrimeViz* was shown on both the laptop and external monitor, and we each had control over the application through our respective input devices. We logged the interactions with *GeoVISTA CrimeViz* using Camtasia Studio, a video recording application that records screen interactions; we captured audio backups of the sessions using a voice recorder. We completed testing over five days, with the usability laboratory remaining in the same configuration throughout the period.

Following an initial exploration period, we required participants to answer a set of 15 close-ended benchmark tasks using *GeoVISTA CrimeViz* (**Table 3**). The benchmark tasks were based on the objective-operand pairings included in **Table 2**, with one question generated for each objective (*identify*, *compare*, *rank*, *associate*, and *delineate*) and operand (*space-alone*, *attributes-in-space, space-in-time*) pairing. The questions were worded so that participants could respond with a brief answer containing only a single term or set of terms. The questions also were generated so that the answer was not apparent in the default overview provided when first entering *GeoVISTA CrimeViz*. Before testing began, we first administered a pilot study with two additional stakeholders at the Harrisburg Bureau of Police in order to revise questions that were unclear or poorly worded, that potentially had more than one correct or partially correct answer, and that had answers that participants would be able to recall from experience without first interacting with *GeoVISTA CrimeViz*.

[Table 3 approximately here]

During the interaction study, we read each question aloud and then handed a print of the question to the participant for reference. The order of the questions was randomized, with no two participants receiving the same question order. Unlike the exploration period, we did not allow participants to ask for clarification about *GeoVISTA CrimeViz* while completing the benchmark tasks. Participants instead were directed to limit their verbalizations in order to focus upon the question at hand. Once the participants believed they had found the answer to the question, we instructed participants to state it aloud for the audio recording. We provided participants a maximum of three minutes to answer each question in order to ensure the set of 15 questions was completed in 45 minutes or less; only four of the total 150 questions (15 questions by 10 participants) exceeded the three minute limit, with all participants completing the formal testing component of the interaction study in 20-25 minutes. In the event that the three minute limit was reached, we gave participants the opportunity to provide a best guess before moving to the next question. After an answer was verbalized for a question, or after the three minute time limit expired, we refreshed the browser containing *GeoVISTA CrimeViz* to force the participant to start from the default overview when answering the subsequent question.

3.3 Interaction Analysis

Following testing, we distilled the Camtasia Studio screen recordings of participant interactions into interaction logs for subsequent analysis. To create the interaction logs, we translated the specific functions in the *GeoVISTA CrimeViz* into the general operator and operand primitives they represent. Eight of the twelve work operators and all three of the operands from the Roth (2013a) taxonomy are implemented in *GeoVISTA CrimeViz*. **Table 4** lists each individual interface component in the experimental version of *GeoVISTA CrimeViz* and the associated operator and operand primitives it supports and **Figure 2** annotates the *GeoVISTA CrimeViz* interface components based on the implemented operator and operand primitives.

We analyzed the interaction logs in two stages. In the first stage, we calculated descriptive statistics on the interaction primitives in aggregate form in order to draw broad connections across objectives, operators, and operands. We calculated five performance measures according to objective-operand pairings, as described by Sweeney et al. (1993): (1) the percentage of the questions that were completed (i.e., questions answered prior to reaching the three minute time limit), (2) the accuracy level or error rate of the answers, (3) the time taken to answer each question, (4) the number of operators used to answer the question (i.e., *frequency*), and (5) the range of operators used to answer the question (i.e., *diversity*). In addition to the five objective-operand statistics, we also calculated a pair of measures across operator-operand pairings: (1) each pairing's overall frequency and (2) each pairing’s *extensiveness*, or the number of interaction sessions in which a specific combination was employed.

[Table 4 approximately here]

In the second stage of analysis, we created timeline graphics representing the interaction logs in order to interpret individual interaction strategies and compare competing interaction strategies (Haug, MacEachren, and Hardisty 2001). Interpretation of such timeline graphics can be as difficult as interpreting a text-based table listing the interactions, particularly when interactions performed during a session are both frequent and diverse. To improve interpretation, we developed a novel way to visualize interaction logs, aggregating interactions to a temporal resolution of five seconds and aligning all 10 interaction strategies performed for each objective-operand combination into a single overview figure for comparison. Each applied operator is indicated by a one-letter code and each manipulated operand is indicated by the color (*space-alone* in green, *attributes-in-space* in blue, and *space-in-time* in red). The timestamp of the participant's response also is represented in the timeline graphics, indicated in black with a ‘yes’ (correct) or ‘no’ (incorrect). When multiple operators were performed within a five second timeframe, we stacked them horizontally using the same ordinal-level metaphor employed by a stem-and-leaf information graphic (although it is important to note that interaction codes are not conceptual ‘leaves’ to the timeline's ‘stem’). For each timeline graphic, we sorted the individual participant interaction strategies from ‘successful’ to ‘unsuccessful’ according to the following criteria: (1) correct versus incorrect, (2) completed within three minutes or not, (3) time taken to respond, and (4) number of interactions (applied only when two or more participants took the same amount of time to answer a question).

4 Results and Discussion

4.1 Interacting with *GeoVISTA CrimeViz*

Table 5 provides a summary of participant interactions performed to answer each of the 15 questions included in the interaction study protocol, which again are representative of each possible objective and operand pairing; aggregate metrics also are provided for each objective or operand primitive, as well as all questions in total. Participants performed well overall, answering 123 of the 150 total questions correctly (82%). The high accuracy rating perhaps is a reflection on the high levels of user expertise and motivation, as well as the initial exploration period. Only four of the 150 total questions required the full three minutes; participants were able to provide the correct answer after time had expired in two of these four instances. On average, participants required 1:00 (one minute) and employed 3.4 different operators a total of 7.4 times to answer each question.

The **Table 5** metrics generally indicate an increasing level of difficulty across the objective primitives according to their level of sophistication. The *identify* objective (i.e., the least sophisticated) required the least amount of time overall (0:31) and the fewest interactions (3.1), while the *delineate* objective (i.e., the most sophisticated) required the most amount of time overall (1:27) and the most interactions (9.8); the *delineate* objective also resulted in the most incorrect answers (only 67% accuracy). There was some overlap in the metrics for the objectives of intermediate sophistication. While the *compare* objective overall took slightly longer to complete and resulted in more mistakes than the *rank* objective, the *rank* objective required more frequent and diverse interactions than the *compare* objective. Similarly, while the *rank* objective required more frequent and diverse interactions than the *associate* objective, the *associate* objective took longer to complete and resulted in more errors than the *rank* objective. The *associate* objective proved to be more difficult to complete than the *compare* objective across all five metrics, suggesting that the postulated objective ordering of *identify→compare→rank→associate→delineate* according to their level of sophistication or cognitive difficulty still holds overall.

Regarding the operand component of the questions, participants most easily responded to questions regarding the *space-alone* operand; this finding holds across all five metrics. Summary metrics regarding the *attributes-in-space* and *space-in-time* operands were similar, with participants requiring slightly more time to respond to questions including the *attribute-in-space* operand and slightly more frequent and diverse interactions to respond to questions including the *space-in-time* operand. Interestingly, participants only had problems answering questions about the *attribute-in-space* operand within the allotted three minute time limit, but were considerably less accurate in their responses to questions about the *space-in-time* operand.

[Table 5 approximately here]

In contrast, **Table 6** provides a summary of the operators employed to answer each of the 15 questions (rather than performance on the questions themselves), discriminated according to the operand on which they were performed. The *retrieve* operator was the most frequently and extensively applied operator primitive (frequency=395, extensiveness=71%), followed by the *filter* (frequency=240, extensiveness=60%) and *zoom* (frequency=127, extensiveness=44%) operators respectively; no other operators were used in more than one-third of the 150 interaction strategies. Such an emphasis of *retrieve*, *filter*, and *zoom* supports Shneiderman's (1996) visual information seeking mantra, in which the *filter* and *zoom* operators are used to transition from an overview to a details view, with the *retrieve* operator then applied to extract specific information from the details view. As discussed in the following subsection, however, the *filter*, *zoom*, and *retrieve* operators (as well as the *pan* operator, which typically is applied in tandem with *zoom*) often were employed unproductively, and instead may indicate that the user does not know how to find the answer to his or her question.

[Table 6 approximately here]

Regarding the operand on which the operator is applied, participants least commonly interacted with the *space-alone* operand (frequency=175, extensive=33%); several of the cartographic interfaces provided to manipulate the *space-alone* operand were ignored altogether (e.g., *search* and *overlay* by *space-alone*). This perhaps is explained by the increased difficulty in answering protocol questions regarding the *attributes-in-space* and *space-in-time* operands, as many more interactions were performed to answer the questions about either attribute or time in comparison to questions about space (**Table 5**). However, this may be true about all map-based interactions generally, as a map first and foremost is a spatial representation and thus ostensibly supports many spatial map reading questions without digital interaction. Therefore, it may be more important to provide (and design well) cartographic interfaces to manipulate the *attributes-in-space* and *space-in-time* operands than the *space-alone* operand, given the intrinsic spatial quality of a map. Finally, an interesting distinction between interactions with the *attributes-in-space* and *space-in-time* operands was observed; while the participants most frequently interacted with the *space-in-time* operand (frequency=543, extensiveness=63%), they most extensively interacted with the *attributes-in-space* operand (frequency=248, extensiveness=78%).

4.2 Prototypically Successful and Unsuccessful Interaction Strategies

Table 5 and **Table 6** describe the cumulative application of operator primitives according to the objective and operand context (i.e., the question from the protocol). In the following, individual interaction strategies are compared for each objective and operand pairing to identify common patterns and prototypically successful interaction strategies. For each objective-operand pairing, a brief summary of the variation across participants and a timeline representation of the interaction logs are provided. Equal emphasis is given to successful and unsuccessful strategies, as key bottlenecks and missteps constituting the latter are important for understanding why one strategy is more effective (i.e., led to a correct answer) or more efficient (i.e., led to a correct answer more quickly) than others. Where possible, ***personas*** are developed to characterize chronic issues in applying operators that occurred across participants and across tasks. These personas are an important product of the interaction study, as they provide a generalization of suboptimal interaction strategies that we hypothesize will be applicable across a wide array of geovisual analytical applications.

#1. *Identify* by *Space-Alone*: On what street did incident #20101100945 occur? (*space-alone*)

There was little variation across participants in the operators employed to answer the *identify* by *space-alone* question (#1; **Figure 3**); all participants were able to answer this question correctly and within 30 seconds. The prototypically successful interaction strategy consisted entirely of the *search* operator, specifically the *GeoVISTA CrimeViz* form fill-in interface for searching by the crime incident report number that is included in the Data Panel. Generally, the faster the participant could type the crime incident report number into the *search* interface, the sooner he or she answered the question. The least efficient strategies were those that included additional operators (e.g., *retrieve* by Participant G and *filter* by Participant E), although this resulted in only a minimal loss of efficiency for the *identify* by *space-alone* question (#1).

[Figure 3 approximately here]

#2. *Identify* by *Attributes-in-Space*: What type of crime (by uniform crime reporting, or UCR, code) is incident #20101100894, which occurred at 200 Herr Street?

As with the *identify* by *space-alone* question (#1), there was little variation across participants in the operators employed to answer the *identify* by *attributes-in-space* question (#2; **Figure 4**). Again, all participants were able to answer the question correctly, although four participants required more than 30 seconds (and one required more than a minute). Interestingly, all participants chose to apply the *search* operator, although a response did not immediately follow application of the operator in all cases, perhaps indicating a greater difficulty in extracting the attribute information from the *GeoVISTA CrimeViz* information window design, as compared to the spatial information extracted during the *identify* by *attributes-in-space* question (#2). All participants searched by the crime incident report number (i.e., *search* by *attributes-in-space*, or a blue 'S' in the interaction log) rather than searching by the street address (i.e., *search* by *attributes-in-space*, or a green 'S' in the interaction log), even though both components were included in the question (unlike the *identify* by *space-alone* question, #1, above, which included the crime incident report number only). Participants searched by the report number rather than the street address to answer all questions in the protocol (i.e., there were zero applications of *search* by *space-alone*, as shown in **Table 4**), despite opportunities to do otherwise (or to perform both). This perhaps is explained by the participants' familiarity in working with their own crime incident reports, but not with maps of these reports. Regardless, the clear reliance on the *search* operator for the *identify* by *space*-alone (#1) and *attributes-in-space* (#2) questions provides initial evidence that the *identify* objective should be supported by the *search* operator, when possible.

Application of additional operators for the *identify* by *space-alone* question (#1) did impose noticeable differences in efficiency; the three participants that performed operators other than *search* required 15-45 seconds longer to answer the question than their counterparts that applied *search* only. As with the *identify* by *space-alone* question (#1), Participant E curiously did not answer until after first narrowing into a specific time range using the *filter* by *space-in-time*, even when all information needed to answer a question was included in the display. Such an application of the *filter* operator negatively impacts productivity and may be part of a routine (at least for Participant E) when moving from an overview to a details view. This interaction strategy allowed us to define our first user persona, the ***excessive-filterer***: interaction behavior in which the *filter* operator is unnecessarily applied for simpler objectives as part of a routine (i.e., while following the visual information seeking mantra), negatively impacting productivity due to the computing time and cognitive workload required to process the *filter* result.

[Figure 4 approximately here]

#3. *Identify* by *Space-in-Time*: How many total crime incidents occurred in District #5 on September 1st, 2010?

Unlike the other questions representative of *identify* objectives (#1 and #2), the *identify* by *space-in-time* question (#3) proved to be difficult (only 6 of 10 participants answered correctly) and resulted in several competing interaction strategies (**Figure 5**). Five of the six participants that correctly answered the question applied the *filter* operator to both the *space-alone* operand (i.e., numerical stepper to *filter* by Police District) and *space-in-time* operand (i.e., numerical steppers to *filter* linearly in time), appropriately moving from the overview map to a details view showing only the correct spatiotemporal extent. Participants were forced to use the *filter* operator for the *identify* by *space-in-time* (#3) question because a temporal *search* was not provided in the experimental version of *GeoVISTA CrimeViz*, a shortcoming of the interface design (**Table 4**). Participant I was able to answer the question correctly by substituting *filter* by *space-alone* with the *zoom* and *pan* operators (i.e., ***map browsing***), both in *space-alone*; participants were able to recover when applying this solution to objectives of lesser sophistication (e.g., *identify* and *compare*), but not for objectives of increased sophistication (as described below). Rapid application of *zoom* did not prove successful for Participant A regarding the *identify* by *space-in-time* question (#3).

Interestingly, Participant F did successfully apply the *filter* operator to both operands, but followed these operators with a rapid series of *retrieve* operators and ultimately failed to find the correct answer. The *retrieve* operator was applied by Participant G to answer the *identify* by *space-alone* question (#1) and Participants J, C, and E to answer the *identify* by *attributes-in-space* question (#2); in both cases, only a single *retrieve* operator was applied to confirm the correct answer, impacting efficiency by only 10-15 seconds. Thus, while a single, purposeful application of the *retrieve* operator decreases productivity slightly, it acts to acquire the correct answer or to improve the user's confidence in the answer, and therefore is not a suboptimal interaction strategy generally. However, the rapid application of the *retrieve* operator by Participant F did not lead to a correct answer. This rapid application of *retrieve* instead was indicative of anxious behavior applied when the *filter* operators did not result in an obvious answer in the map, leading the participant to probe the map in hope of finding the answer. The negative interaction strategy led us to define our second user persona, the ***unsure-retriever***: interaction behavior in which the *retrieve* operator is applied in rapid succession, suggesting a situation in which the user does not know how the *filter* tools support proper refinement of the mapped features

The *unsure-retriever* persona is most evident in *identify* objectives, for which the target is a single map feature. Such a suboptimal interaction strategy is prompted by a breakdown in Shneiderman's (1996) visual information seeking mantra, or when the application of the *filter* or *zoom* operators did not yield the expected details, thus indicating that navigation between an overview and details view is two-way and that strong orientation cues are needed in the interface design to maintain a portion of the overview or to indicate how to return to the overview (Harrower and Sheesley 2005). That such a breakdown may happen is additional evidence for supporting the *search* operator over the *filter* (e.g., the misstep by Participant F) and *zoom* (e.g., the misstep by Participant A) operators for the *identify* objective. This specific example of the *unsure-retriever* persona was prompted by application of incorrect visual isomorphs—or representations of equivalent information in a different visual structure—using the *reexpress* operator (specifically, the use of a composite rather than a linear view of time), an issue described in more detail below.

[Figure 5 approximately here]

#4. *Compare* by *Space-Alone*: Are Fire Station #2 and Fire Station #8 in the same police district?

Participants overall performed well on the *compare* by *space-alone* question (#4) with 9 of the 10 participants answering correctly and all participants answering within 45 seconds (**Figure 6**). The prototypically successful interaction strategy included application of the *overlay* and *retrieve* operators.

All participants applied the *retrieve* operator three to six times, illustrating that rapid application of *retrieve* does not necessarily indicate the *unsure-retriever* persona when performed to answer a *compare* objective (or objectives at a higher level of sophistication); however, it is important to note that the number of applications of *retrieve* generally increases from three with an equal increase in response time, as some participants could not remember the initially retrieved values.

Of the participants that applied the *zoom* operator, most participants applied it only following application of the *overlay* operator. Generally, it is recommended to apply the *overlay* operator prior to applying the *zoom* operator, rather than vice versa, as the initial application of *overlay* provides important contextual information for the subsequent application of *zoom*, ultimately supporting an informed transition from an overview to a details view. The only potential negative of such a strategy is the plotting of a voluminous contextual dataset, producing a cluttered view and a potential system response delay that together hinder the appropriate application of the *zoom* operator (cartographic design of an overview representation for the context layer alleviates this issue). Participant G illustrates the potential problems with applying *zoom* prior to *overlay***,** as he or she ultimately had to apply the *pan* operator to recenter the view on the compared map features, delaying the response. This negative interaction strategy allowed us to define a third user persona, the ***uninformed-zoomer***: interaction behavior in which the *zoom* operator is applied without the proper context provided by the *overlay* operator, resulting in user confusion about what he or she is viewing.

[Figure 6 approximately here]

#5. *Compare* by *Attributes-in-Space*: Is incident #20101100945, which occurred on Market Street, the same type of crime (by uniform crime reporting, or UCR, code) as incident #20101100608, which occurred on 3rd Street?

As with the *compare* by *space-alone* question (#4), participants performed well on the *compare* by *attributes-in-space* question (#5), with all 10 participants answering the question correctly and 7 of 10 participants answering within 60 seconds (**Figure 7**). The prototypical interaction strategy included a pair of *search* operators, effectively resulting in the doubling of the prototypical interaction strategy for the *identify* by *attributes-in-space* (#2) question, which included only a single application of *search*. The relationship between the *identify* (#2) and *compare* (#5) interaction strategies further supports Crampton's (2002) postulation that a more sophisticated objective may be compartmentalized into a series of less sophisticated objectives to simplify the task or to make it easier to determine an optimal interaction strategy.

Interestingly, Participants A and C applied the *search* operator three or more times, resulting in a response time 30-45 seconds longer than their counterparts applying the *search* operator only twice. This delay was caused by mistyping the crime incident report number into the form fill-in search interface, a productivity issue associated with the added flexibility of the form fill-in interface style. Both Participant I and Participant G behaved as *excessive-filterers*, starting the session with an unnecessary *filter* by *space-in-time*.

Participant I followed the *filter* operator with a series of *zoom*, *pan*, and *retrieve* operators. Although, Participant I was able to find the correct answer, this participant did so less quickly than participants applying the *search* operator twice without misspellings. This interaction strategy led to our fourth user persona, the ***lost-browser***: interaction behavior in which the *zoom* and *pan* operators are applied in rapid succession, indicating that the user is disoriented by the current map view. As noted below, the *lost-browser* persona was observed more frequently as the objective increased in sophistication.

[Figure 7 approximately here]

#6. *Compare* by *Space-in-Time*: In October 2010, how many more crime incidents occurred within Harrisburg on Sundays compared to Mondays?

Interaction strategies performed to answer the *compare* by *space-in-time* question (#6) were among the most complex exhibited during the interaction study (**Figure 8**); only 6 of 10 participants correctly answered the question (tied for the second lowest accuracy) and participants used on average 11.2 operators per session (tied for the second most), but no operators were applied to the *space-alone* or *attributes-in-space* operand (as with most of the questions concerning the *space-in-time* operand). The key to completing the *compare* by *space-in-time* question was generation of the proper visual isomorph using the *reexpress* operator, in this case a composite week by day of the week. Overall, the more quickly the *reexpress* operator was performed to generate the appropriate visual isomorph, the more quickly the participant was able to respond. For instance, Participant H and G first applied several *filter* operators—again, likely out of habit, representing the *excessive-filterer* persona—which delayed response by 30-90 seconds compared to Participants I, B, D, and E.

The four participants that answered incorrectly were not able to generate the appropriate visual isomorph: Participant A applied the incorrect visual isomorph and never changed it, Participants J and F changed the visual isomorph multiple times, but never evoked the composite week by day of the week visual isomorph, and Participant C did not change the visual isomorph from a linear timeline. These interaction strategies allowed us to define a fifth user persona, the ***mistaken-reexpresser***: interaction behavior in which the *reexpress* operator is applied to generate an inappropriate representation for the user objective, leading to misinterpretation of the provided visualization. The overall difficulty in applying the *reexpress* operator to identify the optimal visual isomorph likely explains the poor accuracy levels exhibited by participants on questions concerning the *space-in-time* operand (70%), as compared to questions concerning the *space-alone* (94%) and *attributes-in-space* (82%) operands (**Table 3**), as the *reexpress* operator was only available for manipulation of the *space-in-time* operand.

Following generation of the appropriate visual isomorph using the *reexpress* operator, participants then needed to apply the *filter* operator to limit the linear temporal extent and the *retrieve* operator to extract the frequency either in the temporal histogram or in the map view. All participants retrieved details through the temporal histogram instead of the map view, the more efficient choice as participants would have had to add the frequencies of the hexagons using multiple applications of *retrieve* to *attributes-in-space*. The use of the *retrieve* operator between participants that answered the *compare* by *space-in-time* question (#6) correctly versus incorrectly demonstrates the difference between a targeted, informed use of *retrieve* and an anxious, unsure use of *retrieve* (i.e., the *unsure-retriever* persona; see Participants J, F, and C in particular).

[Figure 8 approximately here]

#7. *Rank* by *Space-Alone*: What school in Harrisburg is closest to Interstate-83?

Performance on the *rank* by *space-alone* question (#7) was good, with 9 of 10 participants answering correctly and 7 of 10 participants answering within 45 seconds (**Figure 9**). Overall, the interaction strategies performed for the *rank* by *space-alone* question were very similar to the *compare* by *space-alone* question, again indicating the possibility of decomposing sophisticated objectives into a set of less sophisticated and more easily managed objectives. Successful participants first performed the *overlay* operator to display contextual information when subsequently applying the *zoom* operator.

After applying the *overlay* operator, most participants zoomed to a specific area based on the overlaid context information, but then spent 5-10 seconds panning to neighboring areas to double-check their answer before responding. Participant A failed to apply the *overlay* operator at the start of the session, instead applying the *pan* and *retrieve* operators without context information; as a result, Participant A exhibited characteristics of the *lost-browser* persona for approximately one minute, as indicated by the continuous, but relatively slow application of *pan* and *zoom* operators.

Interestingly, the lone incorrect response was caused by failure to zoom into a large enough cartographic scale; Participant H used the '+' button to *zoom* into the map, which only jumps one scale level, compared to the direct manipulation of a hexagon bin or map feature used by other participants, which jumps four scale levels. As a result, the overlaid context layer was occluded by the crime incident information in the area of interest, leading the participant to focus on a different area of the map. All participants completed their interaction strategy with a single *retrieve* operator, indicating a purposeful extraction of the map feature of interest.

[Figure 9 approximately here]

#8. *Rank* by *Attributes-in-Space*: Which crime type (by uniform crime reporting, or UCR, code) was the most common in District #1 on November 5th, 2010?

All 10 participants answered the *rank* by *attributes-in-space* question (#8) correctly, although the solutions were split between two competing strategies (**Figure 10**). A first subset of participants (Participant B, I, and G) relied on the *overlay* operator by *attributes-in-space* to determine the extent of each Police District, examining the crime incidents in comparison to this context layer, while a second subset of participants (Participants H, D, F, E, and C) relied on the *filter* operator by *space-alone* to isolate crime incidents only occurring within the Police District under investigation. Participant J applied both operators while Participant A succeeded without applying either.

Unexpectedly, the second strategy leveraging the *filter* operator took approximately 60% longer compared to the first strategy using *overlay* (average of 0:54 seconds for Participants B, I, and G; average of 1:28 seconds for Participants H, D, F, E, and C). This difference in efficiency perhaps is explained by the fact that most participants followed either *overlay* or *filter* with a *zoom* in *space-alone* operator to inspect the details view of the crime incident dataset. Participants first applying *overlay* only applied *zoom* once and did not apply *pan*, while the majority of the participants (although not all) that first applied *filter* were forced to apply *zoom* two or more times, as well as the *pan* operator. As discussed with regard to the *compare* by *space-alone* question (#4), the *overlay* operator provides the important context needed to apply the *zoom* operator appropriately. The application of the *filter* operator did not provide this context in this case, resulting in behavior indicative of the *uninformed-zoomer* persona and, ultimately, the *lost-browser* persona, as in the case of Participant C, the least efficient of the 10 participants.

[Figure 10 approximately here]

#9. *Rank* by *Space-in-Time*: From 2006 through 2010 (i.e., the complete time span), which month exhibited the highest frequency of crime incidents across Harrisburg?

Nine of the ten participants correctly responded to the *rank* by *space-in-time* question (#9; **Figure 11**), the highest accuracy rate exhibited across questions concerning the *space-time* operand. Successful interactions were contingent upon identification of the correct visual isomorph (here, a composite year by month) using the *reexpress* operator, as with the *compare* by *space-in-time* question (#6). Nine of the ten participants generated a composite year by month in either their first or second application of the *reexpress* operator. All six participants that applied the *reexpress* operator twice (Participants E, B, F, C, J, and D) first generated a composite month by day of the month, indicating the potential confusion between the overall composite being created (in this case, a year) and the binning unit within the composite (in this case, a month).

Participant G also generated a composite month by day of the month with the first application of the *reexpress* operator, but did not appropriately apply the *reexpress* operator a second time to generate the correct visual isomorph, ultimately leading Participant G to provide an incorrect response following the *mistaken-reexpresser* persona. The rapid application of the *retrieve* and *pan* at the end of Participant G's session indicates behavior of the *unsure-retriever* persona, clearly caused by the generation of an unhelpful visual isomorph and the associated uncertainty in requesting the appropriate visual isomorph. It is important to note that 6 of the 10 participants (Participants I, E, F, C, J, and D) first applied the *filter* operator to adjust the linear extent, despite the *reexpress* operator adjusting the extent by default when requesting a composite year by month; this behavior again is indicative of the filter-first attitude of the *excessive-filterer* persona.

[Figure 11 approximately here]

#10. *Associate* by *Space-Alone*: Which route should Harrisburg citizens take to get to the west bank of the Susquehanna River during an evacuation related to Three Mile Island?

The *associate* by *space-alone* question (#10: **Figure 12)** proved to be among the easiest included in the protocol (tied for the shortest average response at 0:18; third in frequency and diversity of supporting interactions at 3.0 and 1.6 respectively). The reason for the relative ease in completing the question, despite the relatively sophisticated nature of the *associate* operator, is that the answer could be acquired from one of the included contextual layers without any additional cognitive effort. All participants immediately recognized this solution, applying the *overlay* operator within the first 10 seconds of the session, rather than trying to derive the information mentally. Six participants were able to ascertain the correct answer by applying the *overlay* operator alone, as they did not need to view the map road labels provided only at the larger cartographic scales, given their familiarity with the City of Harrisburg. A seventh participant (Participant E) applied the *pan* operator to recenter on the location of the answer, but also did not need to apply the *zoom* operator to read the labels. The other three participants (Participant A, F, and G) used the *zoom* operator to confirm their answer.

A clear example of the *lost-browser* persona occurred when Participant G was applying *zoom* to confirm his or her response. The initial application of *zoom* was applied to the opposite side of the Susquehanna River as Harrisburg (near the City of Enola, on the west bank), zooming the map to an area with which the participant was less familiar. Participant G initially applied *pan* to move the map in the opposite direction of the desired location, only correcting map browsing when centering upon a known landmark. Thus, it is possible to apply the *overlay* operator prior to *zoom*, but still subsequently apply the *zoom* operator in an uninformed manner.

[Figure 12 approximately here]

#11. *Associate* by *Attributes-in-Space*: From 2006 through 2010 (i.e., the complete time span), is the geographic pattern of prostitution (16) related to the geographic pattern of sex offenses (17)?

The *associate* by *attributes-in-space* question (#11) was much more challenging than the *associate* by *space-alone* question (#10), although 8 of the 10 participants still responded correctly (**Figure 13**). The *filter* operator was essential for completion of the *associate* by *attributes-in-space* question (#11), with all participants applying the *filter* operator to both the *attributes-in-time* and *space-in-time* operands. Compared to the excessive uses of *filter* to complete the *identify*, *compare*, and even *rank* objectives, the application of *filter* is justified for the *associate* objective, as participants needed to view and evaluate the distributions of different subsets of crime incidents in order to characterize their relationship. *Filter* also is essential for the *associate* by *space-in-time* question (#12), and, especially, the three questions including a *delineate* objective (#13-15). Thus, it is possible that the *search* operator better supports the less sophisticated objectives (e.g., *identify*, *compare*, and possibly *rank*) while the *filter* operator better supports the more sophisticated objectives (e.g., *associate* and *delineate*). The *search* operator was not applied in support of any questions including the *rank*, *associate*, or *delineate* objectives. Successful participants also applied *reexpress* or *zoom* to increase the number of crime incidents included in each temporal bin, and thus displayed on the map at once.

[Figure 13 approximately here]

A clear commonality between the two interaction strategies resulting in incorrect answers is the application of the *sequence* operator to animate the map over time (Participant A and Participant D). Cartographic animation is particularly useful for understanding broad trends over time—an important component of the *associate* objective—but is less appropriate for communicating specific changes, as humans are known to be 'blind' to many of the changes in a dynamic visual scene (Simons and Levin 1997; Goldsberry and Battersby 2009). Application of the *sequence* operator for map animation had mixed results in the interaction study. Participant F applied it successfully, constructing and viewing two separate animations. However, Participant A and Participant D were unable to make sense of the map animation, leading us to define our sixth and final user persona, the ***blind-sequencer***: interaction behavior in which rapid application of the *sequence* operator results in the user missing spatiotemporal patterns depicted in the map view. Participant A quickly abandoned the animation and instead began applying the *retrieve* operator to both the map and the temporal histogram, behavior indicative of the *unsure-retriever* persona. In contrast, Participant D played through several different map animations, spending almost 90 seconds interpreting the animations, and responded confidently, but incorrectly.

#12. *Associate* by *Space-in-Time*: From 2006 through 2010 (i.e., the complete time span), does the daily trend in crime increase or decrease across Harrisburg from noon (12:00) to midnight (24:00)?

The *associate* by *space-in-time* question (#12; **Figure 14**) was among the most challenging in the protocol, tying for the second lowest accuracy rate (only 60%; tied with the *compare* by *space-in-time* question, #6) and the second highest average response time (1:36). Like the *compare* by *space-in-time* (#6) and *rank* by *space-in-time* (#9) questions, successful interaction for the *associate* by *space-in-time* question (#12) was contingent upon selection of the appropriate visual isomorph (composite day by hour of the day). For the six participants that correctly answered the question, the sooner that the participant identified the appropriate visual isomorph, the sooner that he or she was able to respond.

Three of the four participants that responded incorrectly exhibited behavior of the *mistaken-reexpresser* persona. Participants F, J, and A incorrectly requested both composite year by month and composite month by day visual isomorphs. Participant G incorrectly requested a composite year by month visual isomorph and proceeded to exhibit *unsure-retriever* behavior when presented with the unexpected view. Even participants that answered the question correctly exhibited the *mistaken-reexpresser* persona to some degree, as only Participant I displayed the correct visual isomorph on the first application of the *reexpress* operator. It is important to note that of the six participants that correctly answered the question, only Participant D evoked the *sequence* operator to animate through the hour bins. While Participant D was able to interpret the animations correctly—and thus did not succumb to the pitfalls of the *blind-sequencer* persona—he or she required the longest amount of time to respond, both for participants that responded correctly and incorrectly.

[Figure 14 approximately here]

#13. *Delineate* by *Space-Alone*: Which police districts exhibit clusters of increased criminal activity from 2006 through 2010 (i.e., the complete time span)?

Participant performance on the *delineate* by *space-alone* question (#13) overall was good (accuracy of 90%), but the interaction strategies applied to answer the question exhibited a high amount of variation (**Figure 15**). As expected, most of the participants applied the *overlay* operator at some point in the session to plot the Police District contextual data layer. However, the most efficient participant (Participant A) did not do this, perhaps because he or she was able to recall the boundaries from experience without offloading this cognitive process onto the map. Nine of the ten participants applied the *filter* operator by *space-in-time* at least once, usually early in the interaction strategy; such successful application of *filter* provides additional evidence that the *filter* operator increases in importance as the objective increases in sophistication. Interestingly, the three most efficient participants (Participant A, I, and G) applied the *reexpress* operator to generate a composite year by month. It is unclear why the *reexpress* operator provided such an advantage, as the question was not contingent upon selection of a visual isomorph different from the linear timeline. This finding also is counter to *mistaken-reexpresser* behavior exhibited in questions pairing the *compare*, *associate*, and *delineate* objectives with the *space-in-time* operand (questions #6, #12, and #15 respectively). It therefore is possible that misuse of the *reexpress* operator (i.e., the *mistaken-reexpresser* persona) is a larger concern when investigating the *space-time* operand compared to the *space-alone* or *attributes-in-space* operands.

[Figure 15 approximately here]

The *sequence* operator appeared to be effective for answering the *delineate* by *space-alone* question (#13), as all four participants (Participants F, D, C, and H) evoking the operator did respond correctly. Interestingly, Participant B exhibited behavior analogous to the *lost-browser* persona (i.e., rapid application of the *pan* and *zoom* operators) during roughly the final minute of his or her interaction strategy, but applied the browsing operators to the *space-in-time* operand rather than the *space-alone* operand. The lone participant to answer incorrectly misinterpreted his or her application of the *zoom* by *space-in-time*, changing the binning unit to a single day and therefore answering the question with regard to one day of criminal activity instead of the complete five years of crime incident data; it is possible that the participant believed he or she requested a composite view (likely composite week by day of the week), rather than changing the binning unit only through the *zoom* by *space-in-time* operator.

#14. *Delineate* by *Attributes-in-Space*: From 2006 through 2010 (i.e., the complete time span), how many different ways (i.e., how many different *modis operandi*, or MOs) was fraud (11) committed across Harrisburg?

The *delineate* by *attributes-in-space* question (#14; **Figure 16**) was by far the most challenging of the 15 questions included in the protocol, with only 3 of 10 participants answering the question correctly (30% accuracy rate, compared to an overall 82% accuracy rate). Participants required 2:13 to respond on average (the next closest question required 37 seconds less on average to answer), with 3 of the 10 participants requiring the complete three minutes. Frequency and diversity scores also ranked among the highest in the 15 question set (1st and 3rd respectively).

Despite this difficulty, the interaction strategies completed by the three participants that correctly answered the question are remarkably similar. Participants F, J, and B began by applying both the *filter* operator by *space-in-time* to limit the linear extent and the *zoom* operator by *space-in-time* to change the temporal binning unit from day to year. This trio of participants then proceeded to apply the *filter* operator to the *attributes-in-time* operand numerous times, effectively delineating a new category with each application of *filter*. Thus, the interaction strategies of the successful participants exemplify the utility of the *filter* operator for the more sophisticated objectives, especially *delineate*.

[Figure 16 approximately here]

#15. *Delineate* by *Space-in-Time*: The 2008 spike in robbery (03) incidents in Harrisburg spanned across which months?

Overall, performance was much better on the *delineate* by *space-in-time* question (#15; **Figure 17**) as compared to the *delineate* by *attributes-in-space* question (#14), with 8 of 10 participants responding correctly. As with the other questions including the *delineate* objective (#13 and #14), an emphasis was placed on the *filter* operator, applied by all 10 participants early in the interaction strategy to both the *attributes-in-time* and *space-in-time* operands. Interestingly, six of the eight participants that correctly answered the question also applied the *zoom* operator to the *space-in-time* operand at some point in the interaction strategy. All participants also applied a small set of *retrieve* operators to conclude the interaction strategy. Thus, most participants closely followed Shneiderman's (1996) visual information seeking mantra to solve the *delineate* by *space-in-time* question (#15). The primary commonality between participants that incorrectly responded (Participant A and Participant H) is the application of the *reexpress* operator at some point during the second minute of the interaction strategy; as a result, neither participant was able to finish the question within the three minutes. Such behavior is consistent with the *mistaken-reexpresser* persona also observed in questions pairing the *compare* and *associate* objectives with the *space-in-time* operand (questions #6 and #12).

[Figure 17 approximately here]

5. Conclusion

In this paper, we addressed the science of interaction in the context of geovisual analytics. This research built upon our past work to establish a three-stage 'composite' taxonomy of fundamental interaction primitives, with the goal of learning how these primitives are applied in combination to produce successful versus unsuccessful interaction strategies. Specifically, we completed an interaction study with 10 law enforcement personnel at the Harrisburg Bureau of Police using *GeoVISTA CrimeViz* as a 'living laboratory,' with the evaluated benchmark tasks informed by the objective and operand dimensions of the composite taxonomy and the interaction logs coded according to the operator dimension

The experimental results revealed several broad insights about user interaction strategies with geovisual analytics applications. In the first stage of analysis, we calculated descriptive statistics to explore performance by objective, operator, and operand primitives across all ten participants. Performance was good overall, an indication of high user motivation and the positive impact of the opening exploration period to start the interaction session. That said, there was a notable increase in the level of difficulty across objective primitives (*identify→compare→rank→associate→delineate*), matching Crampton's (2002) proposed continuum of cognitive sophistication. Thus, even with a highly motivated and well-trained target user group, all user objectives cannot be treated as equal. Looking across operand primitives, participant performance was impacted when the benchmark tasks requiring engagement with the *attributes-in-time* and *space-in-time* operands, with the fewest interactions and response time required for interpreting *space-alone*. This finding is an important reminder that geovisual analytics does not approach space in isolation, and that greater interface functionality may be required for exploring and analyzing the non-spatial components of the mapped information. Finally, analysis by operator primitives showed a reliance on *filter*, *zoom*, and then *retrieve*, suggesting Shneiderman's (1996) mantra as the guiding interaction strategy employed across participants. However, as revealed by the second stage of analysis, Shneiderman's mantra was a detriment to the overall interaction session when applied for less sophisticated objectives.

In the second stage of analysis, participant interaction strategies were compared for each benchmark task using interaction logs. Through this qualitative analysis, we established six interaction personas characterizing chronic interaction breakdowns: (1) the *blind-sequencer* (interaction behavior in which rapid application of the *sequence* operator results in the user missing spatiotemporal patterns depicted in the map view); (2) the *excessive-filterer* (interaction behavior in which the *filter* operator is unnecessarily applied as part of routine use with the application—such as following Shneiderman's mantra—negatively impacting productivity due to the computing time and cognitive workload required to process the *filter* result); (3) the *lost-browser* (interaction behavior in which the *zoom* and *pan* operators are applied in rapid succession when the user is disoriented by the current map view); (4) the *mistaken-reexpresser* (interaction behavior in which the *reexpress* operator is applied to generate an inappropriate visual isomorph, leading to misinterpretation of the provided visualization); (5) the *uninformed-zoomer* (interaction behavior in which the *zoom* operator is applied without the proper context provided by the *overlay* operator, resulting in user confusion about what he or she is viewing); and (6) *unsure-retriever* (interaction behavior in which the *retrieve* operator is applied in rapid succession, suggesting a time in which the user does not know how the *filter* tools support proper refinement of the mapped features). Notably, our research only exposed negative, suboptimal personas, which in part was due to the generally successful application of *GeoVISTA CrimeViz* for completing the benchmark tasks. Future work is needed to identify complementary, positive, and prototypically successful personas in geovisual analytical contexts that are more complex, multifaceted, and open-ended (and thus that are dominated by suboptimal interaction strategies).

Approaching a science of interaction requires generalizability across interaction contexts. In the following, we distill our research findings into five empirically-derived and potentially generalizable UI/UX design and use guidelines for geovisual analytics:

- ***Primitives Provide Benchmarks:*** Our use of benchmark tasks based on objective-operand combinations yielded practical as well as scientific gains, exposing missing interface functionality in *GeoVISTA CrimeViz* such as a temporal search. By distilling all objective and operand pairings into a representative set of benchmark tasks, it is possible to ensure that an application meets the full spectrum of geovisual analytical tasks it will be asked to support.
- ***Spatial is Special, Time is Tantamount, and Attribute is Analogous***: In the interaction study, participants most easily responded to benchmark tasks including the *space-alone* operand, and also leveraged fewer different operators a lesser number of times to respond to these questions. Because the map is a spatial representation as well as interface for geovisual analytics, it is important to design functionality that enables interaction with the spatial, temporal, and attribute components of the dataset, as well as coordinated visuals that enable exploration and analysis across these components.
- ***Exercise Constraint***: In the interaction study, multiple operators regularly were applied unproductively. Formalizing additional user personas appears to be a particularly promising way of relating interaction primitives to interaction strategies, as the geovisual analytics application can be designed to constrain—or even respond in real-time to—suboptimal interaction strategies.
- ***Focus on Filtering***: Regarding interactive map design, geovisual analytics must differ from common 'slippy' web maps, which often implement the *pan*, *zoom*, *overlay*, and *retrieve* operators. In particular, our interaction study revealed the importance, and potential misuse, of the *filter* operator for geovisual analytics. Flexible filtering in space, time, and attribute is essential for supporting sophisticated user objectives, but the interface requires clearing visual affordances for applying and clearing the filters, as well as a pairing with the *search* operator, in order to avoid obstructing less sophisticated objectives.
- ***Promote the Human-Computer Partnership***: At its core, geovisual analytics is about combining the analytical power of the human and the machine to reason through problems that are difficult

for either to solve in isolation. Therefore, let the computer do much of the hard work for common, but sophisticated objectives. The previously discussed inclusion of an overlay in *GeoVISTA CrimeViz* to support a common *associate* objective is one such example of equalizing the cognitive load of all objectives for the user.

Improving our understanding of the nature of interaction remains a pressing research and development challenge facing geovisual analytics, and the related disciplines of cartography and GIScience. Our research presented here offered several, potentially generalizable insights for improving the design of visual interfaces to computational methods in support of sophisticated human reasoning. Additional research is needed to further tease out the consequential relationships of interaction primitive pairings on the success of interaction strategies and to account for the identified interaction personas in geovisual analytics tools and techniques.

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Table 1: A single interaction with *GeoVISTA CrimeViz* following Norman's (1988) seven stages of interaction.

#	*Stage*	*Example*
1	**Forming the goal**	"I want to explore long-term patterns in criminal activity."
2	**Forming the intention**	"I will start my exploration by seeing if the volume of criminal activity changed from 2009 to 2010."
3	**Specifying an action**	"I will use the temporal filtering tools to narrow the timespan."
4	**Executing an action**	"I will use my keyboard to enter the 'from' and 'to' dates."
The timeline visualization is updated to show the number of crime incidents from 2009-2010 and a map is updated to display an animation of crime incidents across this temporal range.		
5	**Perceiving the state of the system**	"I see that there is more criminal activity in 2010 versus 2009."
6	**Interpreting the state of the system**	"I think this means that there has been a potentially meaningful increase in crime."
7	**Evaluating the outcome**	"I now will modify my goal from broad exploration of long-term patterns across criminal activity to analysis of specific causes of the increase from 2009-2010."

Table 2: The Roth (2013a) taxonomy of interaction primitives. For simplicity, findings from the card sorting study regarding user goals, search levels, and enabling operators were not considered in the research design of the interaction study reported in this paper.

#	*Primitive Name*	*Definition*
Objectives (Increasing in Sophistication in the Order of #1-5)		
1	**Identify**	examine and understand a single feature
2	**Compare**	determine the similarities and differences between two features
3	**Rank**	determine the order or relative position of two or more features
4	**Associate**	determine the relationship between two or more features
5	**Delineate**	organize features into a logical structure, such as categorizing or clustering
Operators		
1	**Reexpress**	set or change the visual isomorph used in the representation or information views linked to the representation
2	**Arrange**	manipulate the layout of a visual isomorph when multiple, typically linked visually isomorphic views are provided
3	**Sequence**	generate an ordered set of related representations, such as in an animation or small multiples
4	**Resymbolize**	set or change the design parameters of a representation form without changing the represented features or the representation form itself
5	**Overlay**	adjust the feature types included in the representation, such as switching between different basemap tilesets or adding new layers on top of a basemap tileset
6	**Reproject**	set or change the projection used to transform the information to a two-dimensional screen
7	**Pan**	change the center of the representation
8	**Zoom**	change the scale and/or resolution of the representation
9	**Filter**	alter the representation, and information views linked to the representation, to indicate features that meet one or a set of user-defined conditions
10	**Search**	alter the representation, and information views linked to the representation, to indicate a particular feature of interest
11	**Retrieve**	request specific details about a feature or features of interest
12	**Calculate**	derive new information about a feature or features of interest
Operands		
1	**Space-Alone**	interact only with the geographic component of the representation
2	**Attributes-in-Space**	interact with the attribute component of the representation to understand how one or several characteristics of a geographic phenomenon varies across space
3	**Space-in-Time**	interact with the temporal component of the representation to understand how a dynamic geographic or spatial phenomenon acts over time

Table 3: The objective-operand benchmark tasks used in the interaction study.

#	*Objective-Operand*	*Question (Answer)*
Identify		
1	**Space-Alone**	On what street did incident #20101100945 occur? (A: Market Street)
2	**Attributes-in-Space**	What type of crime (by UCR code) is incident #20101100894, which occurred at 200 Herr Street? (A: 06-Theft)
3	**Space-in-Time**	How many total crime incidents occurred in District #5 on September 1st, 2010? (A: 7)
Compare		
4	**Space-Alone**	Are Fire Station #2 and Fire Station #8 in the same police district? (A: yes)
5	**Attributes-in-Space**	Is incident #20101100945, which occurred on Market Street, the same type of crime (by UCR) as incident #20101100608, which occurred on 3rd Street? (A: no)
6	**Space-in-Time**	In October 2010, how many more crime incidents occurred within Harrisburg on Sundays compared to Mondays? (A: 26)
Rank		
7	**Space-Alone**	What school in Harrisburg is closest to Interstate-83? (A: Sylvan Heights Science Charter School)
8	**Attributes-in-Space**	Which crime type (by UCR code) was the most common in District #1 on November 5th, 2010? (A: 23-Drunkenness)
9	**Space-in-Time**	From 2006 through 2010 (i.e., the complete time span), which month exhibited the highest frequency of crime incidents across Harrisburg? (A: March)
Associate		
10	**Space-Alone**	Which route should Harrisburg citizens take to get to the west bank of the Susquehanna River during an evacuation related to Three Mile Island? (A: I-81 bridge)
11	**Attributes-in-Space**	From 2006 through 2010 (i.e., the complete time span), is the geographic pattern of prostitution (16) related to the geographic pattern of sex offenses (17)? (A: no)
12	**Space-in-Time**	From 2006 through 2010 (i.e., the complete time span), does the trend in crime increase or decrease across Harrisburg from noon (12:00) to midnight (24:00)? (A: decrease)
Delineate		
13	**Space-Alone**	Which police districts exhibit clusters of increased criminal activity from 2006 through 2010 (i.e., the complete time span)? (A: District #1 & District #5)
14	**Attributes-in-Space**	From 2006 through 2010 (i.e., the complete time span), how many different ways (i.e., how many different MOs) was fraud (11) committed across Harrisburg? (A: 7)
15	**Space-in-Time**	The 2008 spike in robbery (03) incidents in Harrisburg spanned across which months? (A: September and October)

Table 4: Operator and Operand Primitives Supported by *GeoVISTA CrimeViz*. In total, *GeoVISTA CrimeViz* supports eight interaction operators: **(this page)** *reexpress* (X), *sequence* (Q), *overlay* (O), and *pan* (P), *zoom* (Z), *filter* (F), *search* (S), and *retrieve* (R). For additional details about *GeoVISTA CrimeViz* functionality, please see: http://www.geovista.psu.edu/CrimeViz/**.**

#	*Operator-Operand*	*Description of Features in GeoVISTA CrimeViz*
1	**Reexpress (X)**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	Menu Selection for Linear versus Composite Time
2	**Arrange**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*
3	**Sequence (Q)**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	Direct Manipulation Click of the 'Play' (Loop) and 'Pause' VCR Controls
4	**Resymbolize**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*
5	**Overlay (O)**	
	Space-Alone	Menu Selection for Basemap Type ('Map', 'Sat', 'Terrain')
	Attributes-in-Space	Menu Selection Checkboxes for Point/Line Data Layers ('Schools', etc.)
		Menu Selection Radio Buttons for Polygonal Data Layers ('Districts', etc.)
		Menu Selection 'Reset' Additional Data Layers
	Space-in-Time	*<none>*
6	**Reproject**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*
7	**Pan (P)**	
	Space-Alone	Direct Manipulation Click+Drag on Map
		Direct Manipulation 'Resent Extent' Control
	Attributes-in-Space	*<none>*
	Space-in-Time	Direct Manipulation Click on Histogram Bin
		Direct Manipulation Click on 'Back' and 'Step' VCR Controls
		Direct Manipulation of Histogram Slider Bar (When Entirety is Not Displayed)
8	**Zoom (Z)**	
	Space-Alone	Direct Manipulation Double-Click on Map
		Direct Manipulation Click on Hexagon Grid
		Direct Manipulation Click on Data Layer Element
		Direct Manipulation '+' and '-' Controls
		Direct Manipulation 'Resent Extent' Control
	Attributes-in-Space	*<none>*
	Space-in-Time	Menu Selection for Binning Unit
9	**Filter (F)**	
	Space-Alone	Menu Selection Numerical Stepper by 'District'
		Form Fill-in by 'District'
		Menu Selection for 'Reset Advanced Features'
	Attributes-in-Space	Menu Selection by 'UCR Primary,' 'UCR Secondary' and 'MO'
		Form Fill-in by 'UCR Primary,' 'UCR Secondary' and 'MO'
		Menu Selection for 'Reset Basic Filters'
	Space-in-Time	Menu Selection Numerical Stepper for 'From' and 'To' Linear Filtering
		Form Fill-in 'From' and 'To' Linear Filtering
		Menu Selection Shortcuts for Linear Filtering ('Week', 'Month', 'Year', 'All')
		Direct Manipulation of 'Hours', 'Months', and 'Days' Widgets for Cyclical Filtering

		Menu Selection Shortcuts for Cyclical Filtering ('All', 'None', 'Winter', etc.)
		Menu Selection for 'Reset Temporal Parameters'
10	**Search (S)**	
	Space-Alone	Form Fill-in Search by 'Address'
	Attributes-in-Space	Form Fill-in Search by 'Report #'
	Space-in-Time	*<none>*
11	**Retrieve (R)**	
	Space-Alone	*<none>*
	Attributes-in-Space	Direct Manipulation Mouse-Over of Hexagon Bin
		Direct Manipulation Mouse-Over of Crime Incident
		Direct Manipulation Click of Crime Incident
		Menu Selection to Activate Street View
		Direct Manipulation Mouse-Over of Data Layer Element
	Space-in-Time	Direct Manipulation Mouse-Over of Histogram Bin
12	**Calculate**	
	Space-Alone	*<none>*
	Attributes-in-Space	*<none>*
	Space-in-Time	*<none>*

Table 5: A Summary of Participant Interactions by Objective and Operand Pairings. Following the recommendations of Sweeney et al. (1993), five summary scores are provided for each question in the cartographic interaction study protocol (i.e., each objective-operand pairing): (1) number and percentage answered within three minutes, (2) number and percentage answered correctly, (3) average time per question, (4) average operator frequency, and (5) average operator diversity. Totals also are provided by individual operator primitive, individual operand primitive, and the study as a whole.

Objective-Operand	*Complete*	*Correct*	*Avg Time*	*Frequency*	*Diversity*
Identify by Space-Alone	10 (100%)	10 (100%)	0:18	1.3	1.2
Identify by Attributes-in-Space	10 (100%)	10 (100%)	0:32	1.6	1.5
Identify by Space-in-Time	10 (100%)	6 (60%)	0:43	6.5	3.6
All Identify	**30 (100%)**	**26 (87%)**	**0:31**	**3.1**	**2.1**
Compare by Space-Alone	10 (100%)	9 (90%)	0:25	7.6	3.0
Compare by Attributes-in-Space	10 (100%)	10 (100%)	0:57	3.5	1.6
Compare Space-in-Time	10 (100%)	6 (60%)	1:32	11.2	3.4
All Compare	**30 (100%)**	**25 (83%)**	**0:58**	**7.4**	**2.7**
Rank by Space-Alone	10 (100%)	9 (90%)	0:42	8.9	3.9
Rank by Attributes-in-Space	9 (90%)	10 (100%)	1:11	11.2	5.1
Rank by Space-in-Time	10 (100%)	9 (90%)	0:53	7.1	3.8
All Rank	**29 (96.7%)**	**28 (93%)**	**0:56**	**9.1**	**4.3**
Associate by Space-Alone	10 (100%)	10 (100%)	0:18	3.0	1.6
Associate by Attributes-in-Space	10 (100%)	8 (80%)	1:24	10.5	5.0
Associate by Space-in-Time	10 (100%)	6 (60%)	1:36	9.2	3.4
All Associate	**30 (100%)**	**24 (80%)**	**1:06**	**7.6**	**3.2**
Delineate by Space-Alone	10 (100%)	9 (90%)	1:08	8.8	4.8
Delineate by Attributes-in-Space	7 (70%)	3 (30%)	2:13	13.6	4.9
Delineate by Space-in-Time	10 (100%)	8 (80%)	1:02	7.0	4.2
All Delineate	**27 (90%)**	**20 (67%)**	**1:27**	**9.8**	**4.6**
All Space-Alone	**50 (100%)**	**47 (94%)**	**0:34**	**5.9**	**2.9**
All Attributes-in-Space	**46 (92%)**	**41 (82%)**	**1:16**	**8.1**	**3.5**
All Space-in-Time	**50 (100%)**	**35 (70%)**	**1:09**	**8.2**	**3.7**
Total	**146 (97%)**	**123 (82%)**	**1:00**	**7.4**	**3.4**

Table 6: A Summary of Participant Interactions by Operator and Operand Pairings. Two summary metrics are provided across operator-operand pairings: (1) frequency (total number of applications across all participants; no maximum) and (2) extensive (total number and percentage of interaction strategies in which the operator was applied; maximum of 150).

Operator-Operand	*Frequency*	*Extensiveness*
Space-in-Time (X)	78	50 (33%)
All Reexpress (X)	**78**	**50 (33%)**
Space-in-Time (Q)	32	14
All Sequence (Q)	**32**	**14 (9%)**
Space-Alone (O)	0	0 (0%)
Attributes-in-Space (O)	57	46 (31%)
All Overlay (O)	**57**	**46 (31%)**
Space-Alone (P)	81	28 (19%)
Space-in-Time (P)	40	17 (11%)
All Pan (P)	**121**	**41 (27%)**
Space-Alone (Z)	82	39 (26%)
Space-in-Time (Z)	45	34 (23%)
All Zoom (Z)	**127**	**66 (44%)**
Space-Alone (F)	12	12 (8%)
Attributes-in-Space (F)	90	31 (21%)
Space-in-Time (F)	138	74 (49%)
All Filter (F)	**240**	**90 (60%)**
Space-Alone (S)	0	0 (0%)
Attributes-in-Space (S)	42	29 (19%)
All Search (S)	**42**	**29 (19%)**
Attributes-in-Space (R)	185	59 (39%)
Space-in-Time (R)	210	58 (39%)
All Retrieve (R)	**395**	**106 (71%)**
All Space-Alone	**175**	**49 (33%)**
All Attributes-in-Space	**248**	**117 (78%)**
All Space-in-Time	**543**	**94 (63%)**
Total	**1092**	**150 (100%)**

Figure 1: *GeoVISTA CrimeViz* (http://www.geovista.psu.edu/CrimeViz)

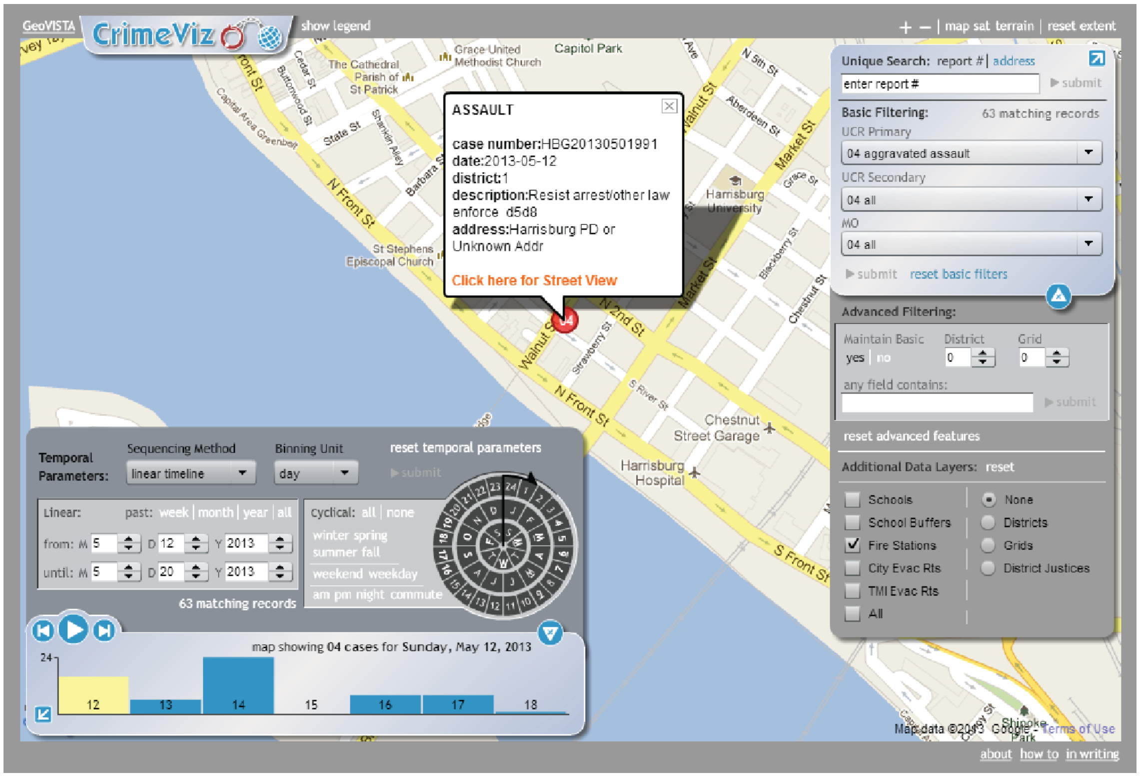

Figure 2. Coding *GeoVISTA CrimeViz* by Interaction Primitive.

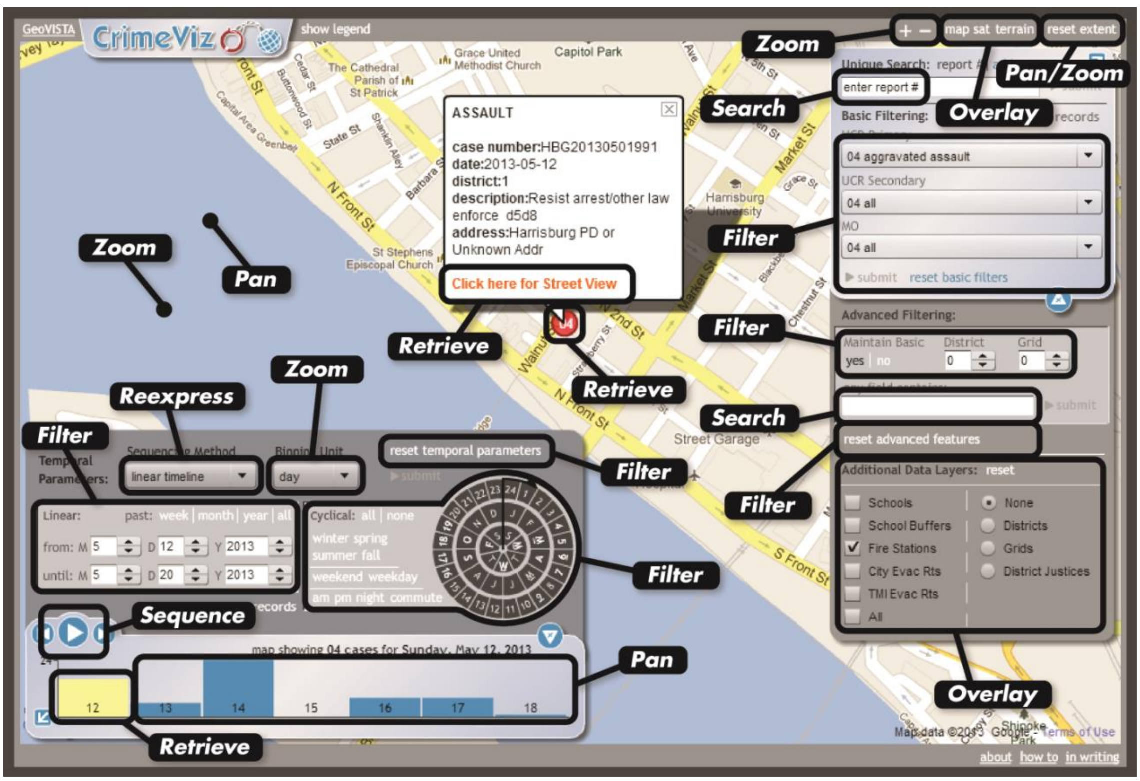

Figure 3: Interaction Logs for *Identify* by *Space-Alone* (#1). In the following interaction log visualizations, operators are aggregated at a temporal resolution of 5 seconds, with time to completion of a benchmark task increasing from top to bottom. The meaning of the single character operator code is provided in Table 4. The participants are ordered from the left (best) to right (worst) based on their performance.

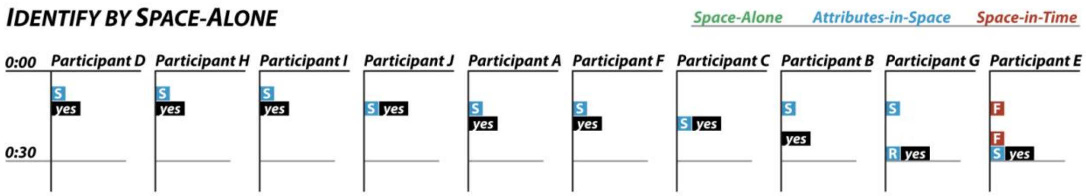

Figure 4: Interaction Logs for *Identify* by *Attributes-in-Space* (#2). Participant E illustrated a prototypical example of the *excessive-filterer* user persona and its negative consequences.

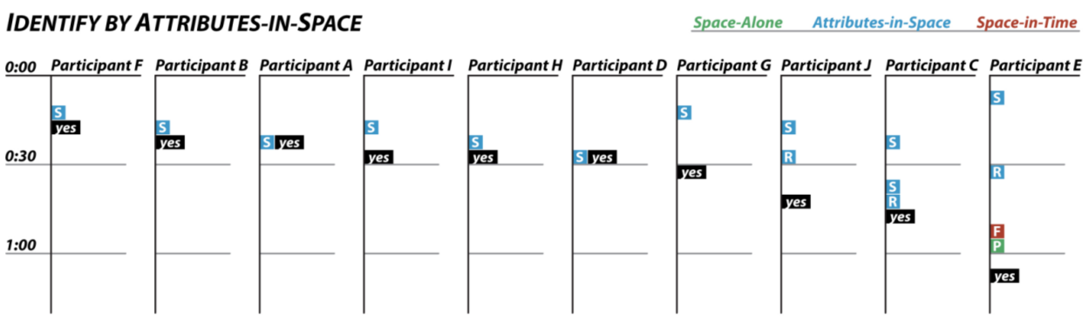

Figure 5: Interaction Logs for *Identify* by *Space-in-Time* (#3). Participant F illustrated a prototypical example of the *unsure-retriever* user persona and its negative consequences.

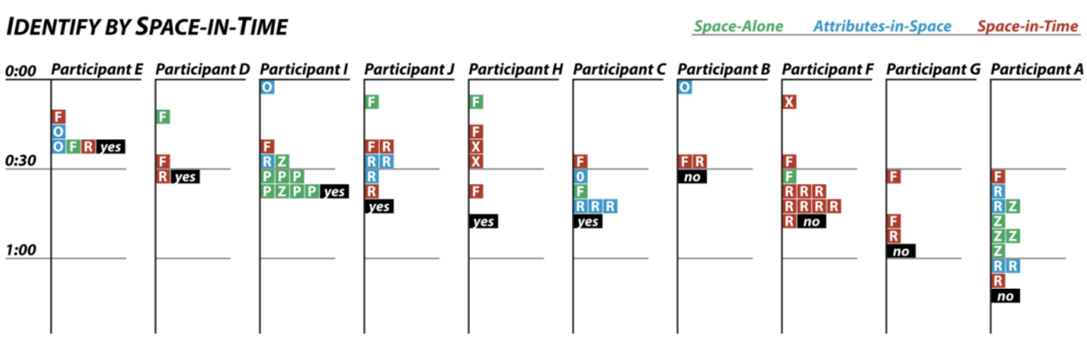

Figure 6: Interaction Logs for *Compare* by *Space-Alone* (#4). Participant G illustrated a prototypical example of the *uninformed zoomer* user persona and its negative consequences.

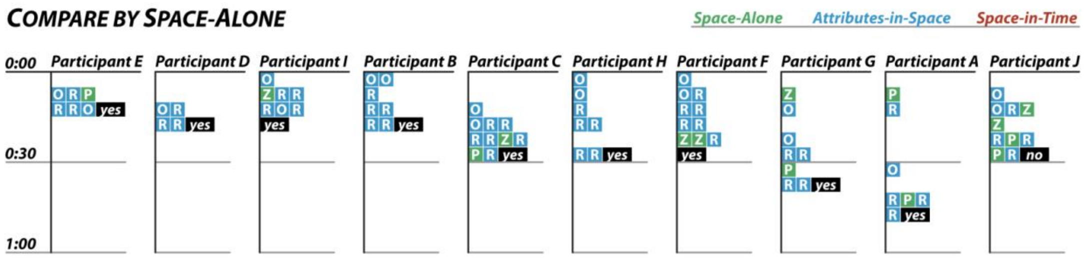

Figure 7: Interaction Logs for *Compare* by *Attributes-in-Space* (#5). Participant I illustrated a prototypical example of the *lost-browser* user persona and its negative consequences.

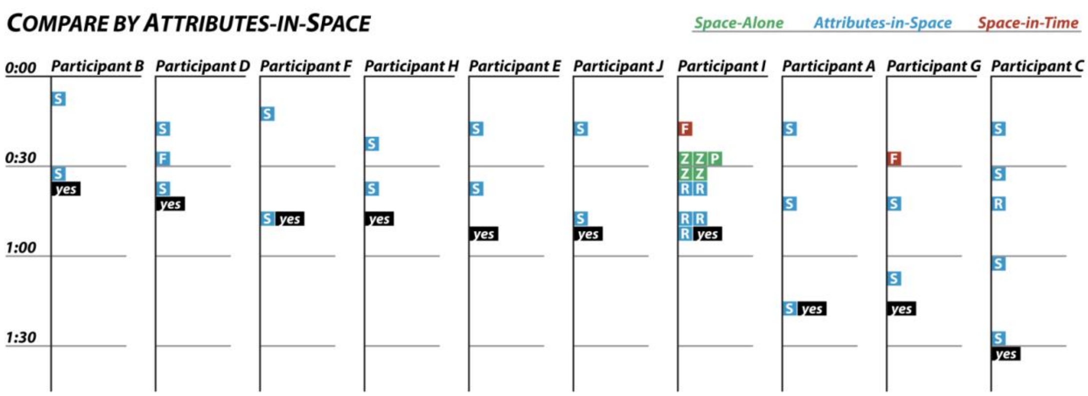

Figure 8: Interaction Logs for *Compare* by *Space-in-Time* (#6). Participants A, J, F, and C illustrated a prototypical example of the *mistaken-reexpresser* user persona and its negative consequences. Participants H and G exhibited behavior of the *excessive-filterer* persona, while Participants J, F, and C exhibited behavior of the *unsure-retriever* persona.

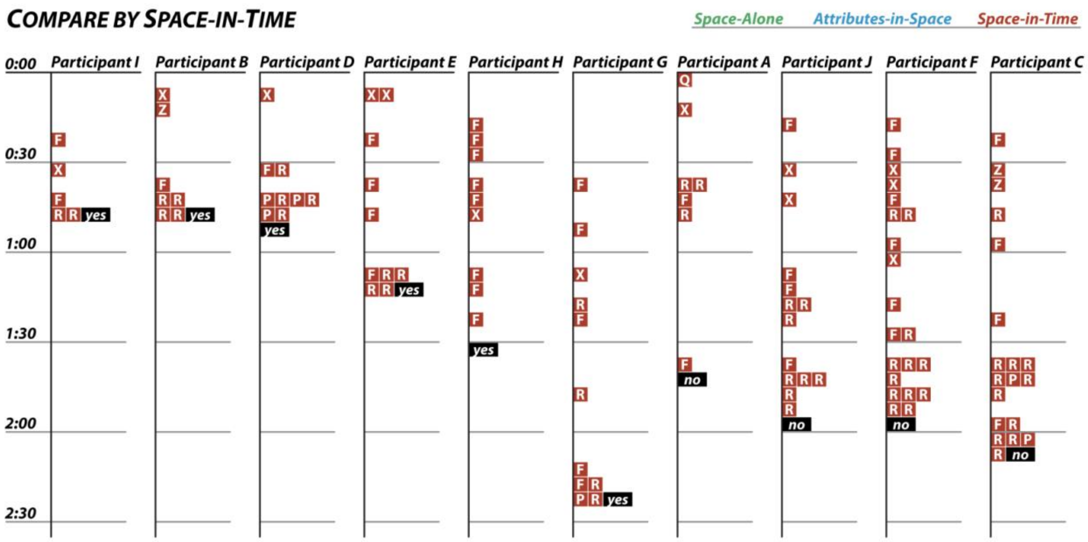

Figure 9: Interaction Logs for *Rank* by *Space-Alone* (#7). Participant A exhibited behavior of the *lost-browser* persona.

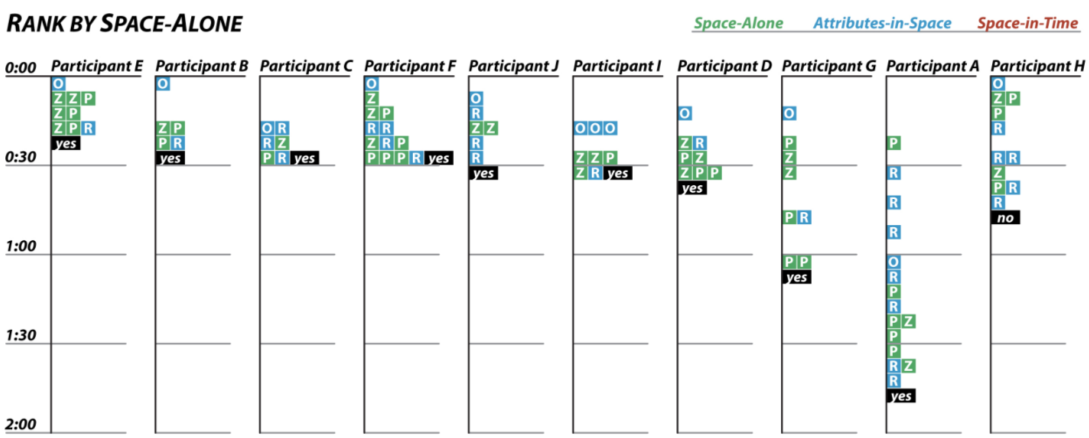

Figure 10: Interaction Logs for *Rank* by *Attributes-in-Space* (#8). Participants H, D, F, E, and C exhibited behavior of the *uninformed-zoomer* persona, while Participants C provided a prototypical example of the *lost-browser* persona.

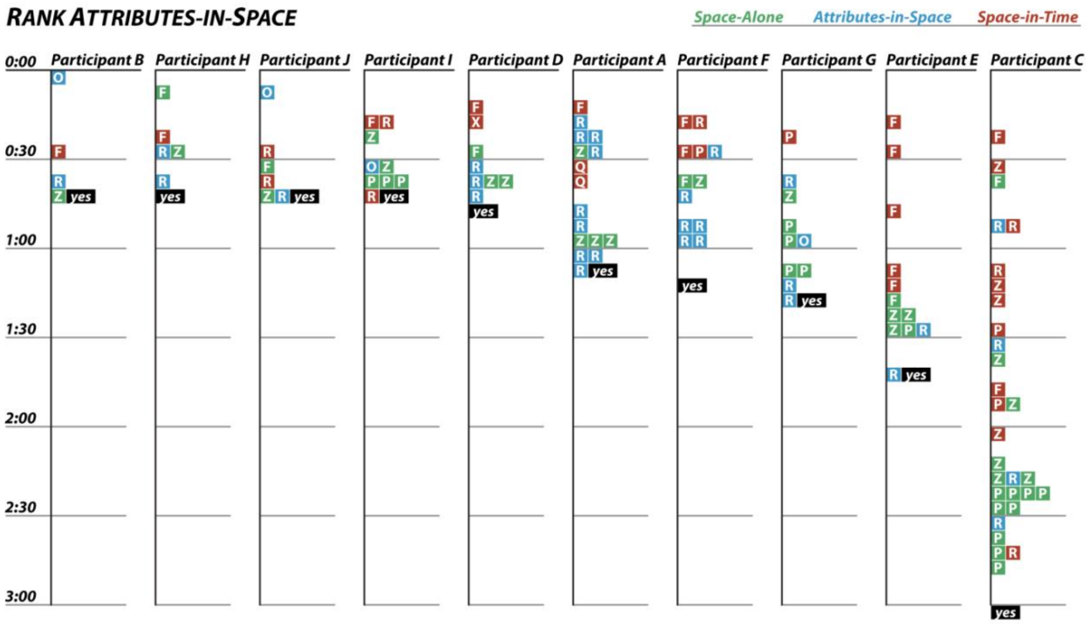

Figure 11: Interaction Logs for *Rank* by *Space-in-Time* (#9). Participant G exhibited behavior of both the *mistaken-reexpresser* and the *unsure-retriever* personas. Participants I, E, F, C, J, and D exhibited behavior of the *excessive-filterer* persona.

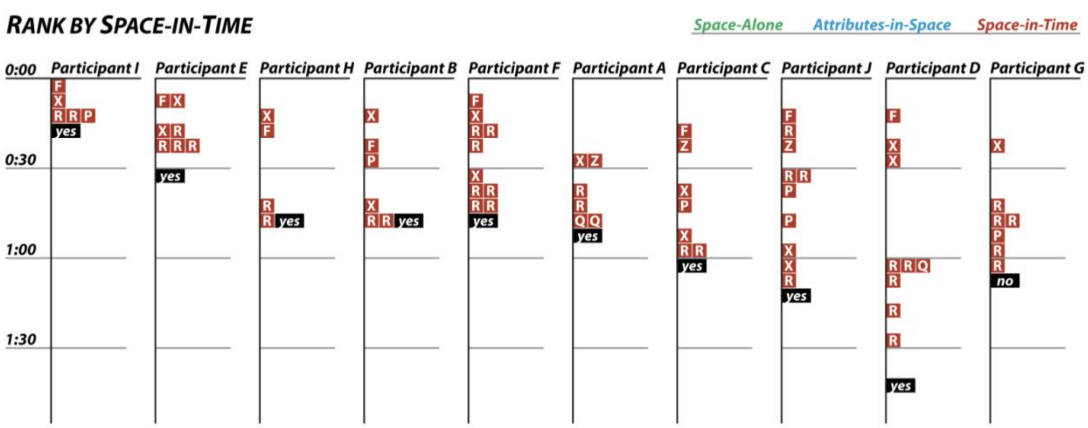

Figure 12: Interaction Logs for *Associate* by *Space-Alone* (#10). Participant G exhibited behavior of the *lost-browser* persona.

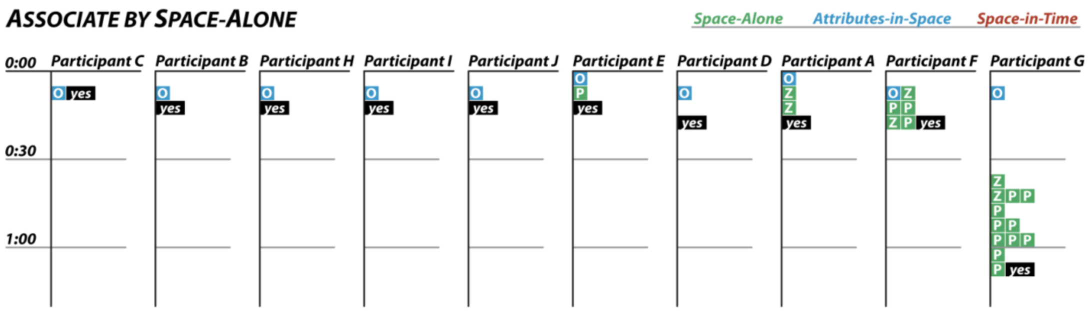

Figure 13: Interaction Logs for *Associate* by *Attributes-in-Space* (#11). Participants A and D illustrated prototypical examples of the *blind-sequencer* user persona and is negative consequences. Participant A also exhibited behavior of the *unsure-retriever* persona.

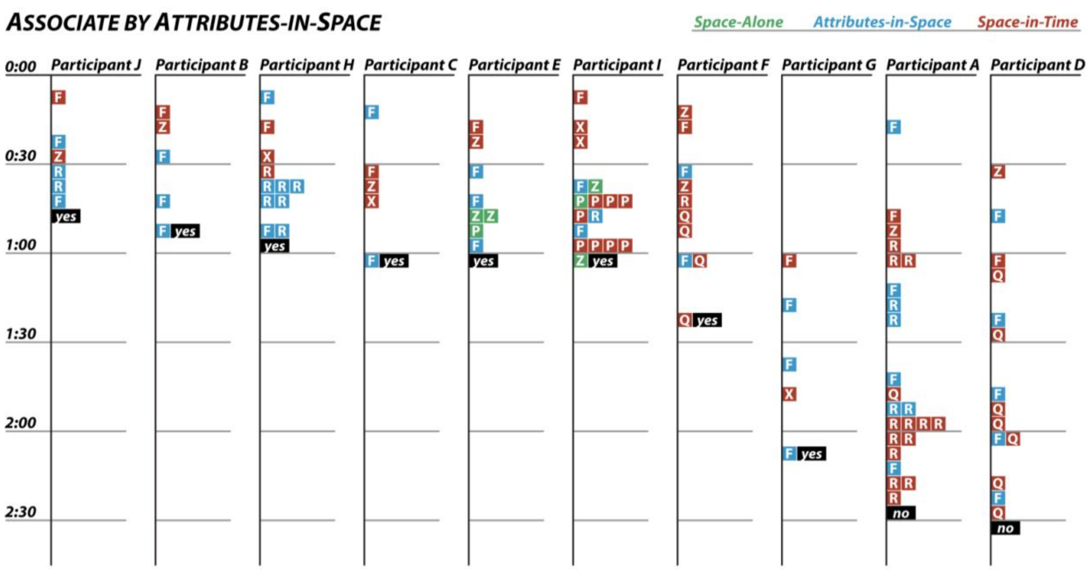

Figure 14: Interaction Logs for *Associate* by *Space-in-Time* (#12). Participants F, J, A, and G exhibited behavior of the mistaken-reexpesser persona, all resulting in incorrect responses. Further, Participant G exhibited behavior of the *unsure-retriever* persona and Participant D exhibited behavior of the *blind-sequencer* persona.

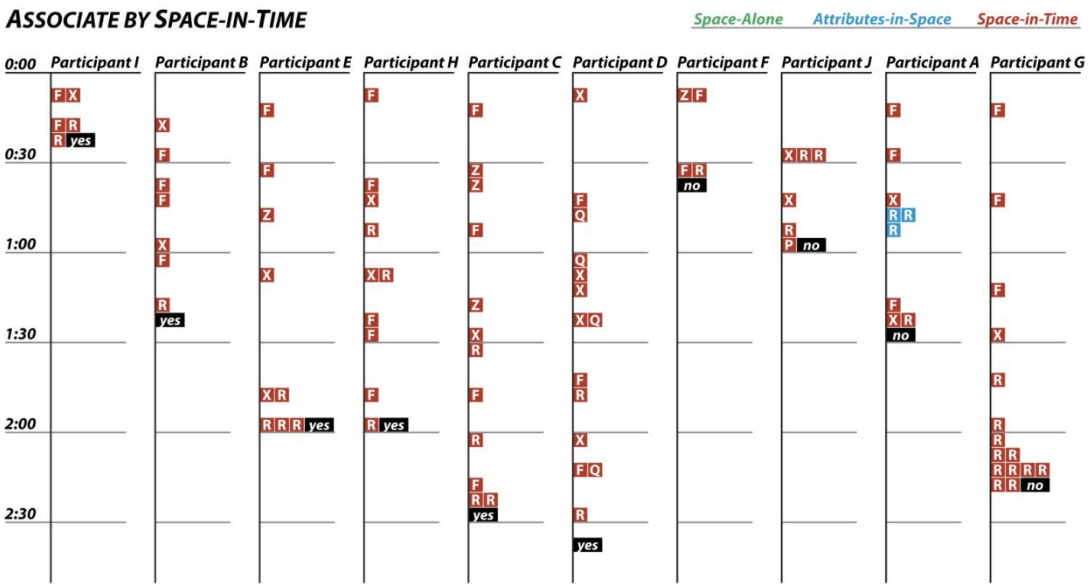

Figure 15: Interaction Logs for *Delineate* by *Space-Alone* (#13). Participant B exhibited the behavior of the *lost-browser* persona.

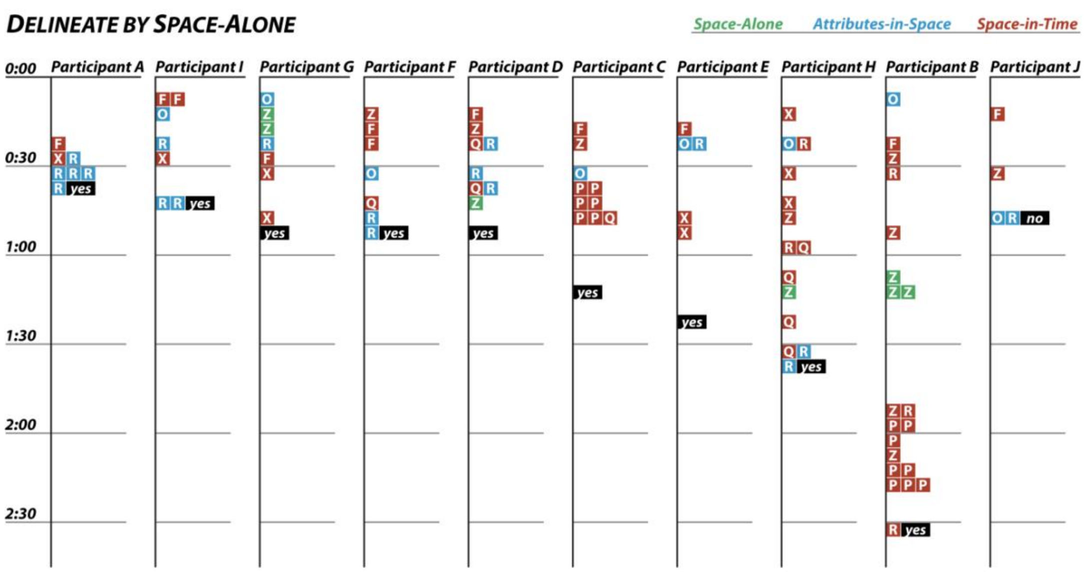

Figure 16: Interaction Logs for *Delineate* by *Attributes-in-Space* (#14).

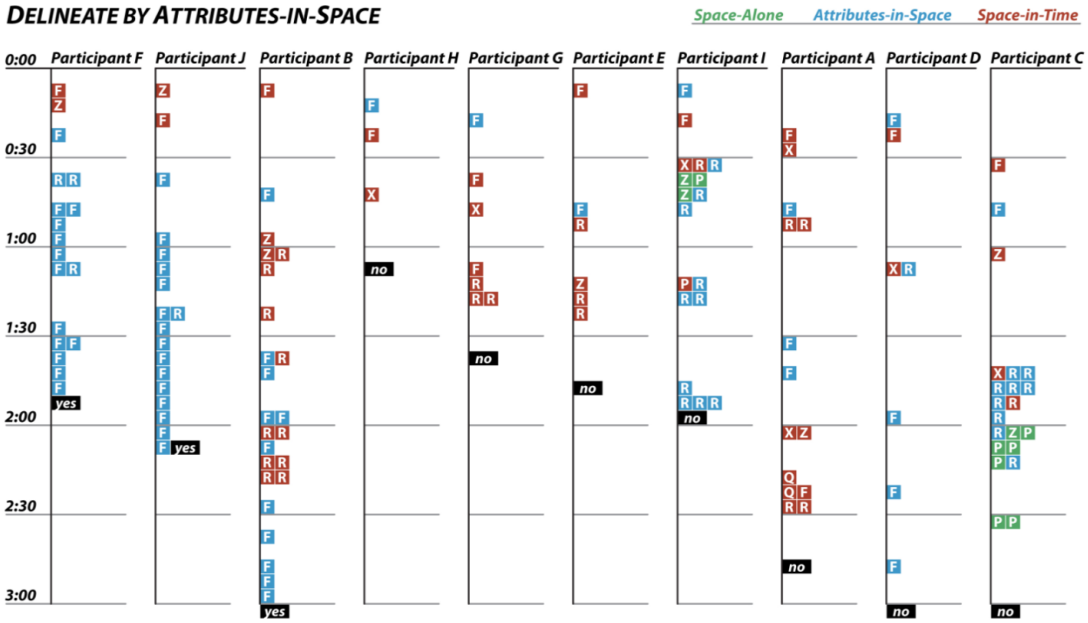

Figure 17: Interaction Logs for *Delineate* by *Space-in-Time* (#15). Participants A and H exhibited behavior of the *mistaken-reexpresser* persona.