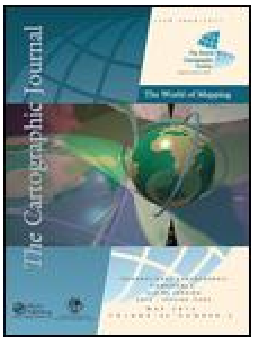

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Cartographic Interaction Primitives: Framework and Synthesis

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A cartographic interaction primitive is a basic unit of interactivity that is combined with other primitives in sequence when using interactive maps. The construction of a taxonomy of these basic interaction primitives is considered the 'grand challenge of interaction', as such taxonomies provide a consistent lexicon for describing map-based interaction strategies and interface designs, inform the design of scientific experiments to investigate the nature of cartographic interaction, and ultimately lead to design and use guidelines for interactive maps. The purpose of this research is not to offer a new framework of interaction primitives—as there are many in existence—but to organize and synthesize extant strategies for parsing interaction within Cartography and the related fields of Human–Computer Interaction, Information Visualisation, and Visual Analytics into a logical framework. Norman's stages of action model provides a useful foundation for conceptualizing interaction primitives, with organisation of extant taxonomies by the model resulting in three dominant approaches for parsing interaction: (1) an objective-based approach, compartmentalizing cartographic interaction according to the kinds of tasks the user may wish to complete with a cartographic interface; (2) an operator-based approach, compartmentalizing cartographic interaction according to the unique cartographic interfaces that make manipulation of a cartographic representation possible; and (3) an operand-based approach, compartmentalizing cartographic interaction according to characteristics of the digital/virtual object with which the user is interacting. Extant interaction primitive taxonomies representative of each of these three approaches are treated in turn, synthesizing key themes within each approach and identifying important concordances and discordances across the associated taxonomies.

Keywords: interactive maps, cartographic interaction, interaction primitives, stages of interaction, objectives, operators, operands, Human–Computer Interaction, Information Visualisation, Visual Analytics

INTRODUCTION: CARTOGRAPHIC INTERACTION AND INTERACTION PRIMITIVES

Maps are inherently interactive. It can be argued that even the first maps and spatial diagrams etched into the sand or scribbled onto a cave wall were interactive (Brown, 1949). Using a stick or piece of charcoal, the mapmaker quickly could adjust the design in response to his or her evolving understanding of the mapped phenomenon, or in response to an inquisitive cave-peer. Similar arguments have been made for less-ephemeral, paper maps as well (e.g., Bertin, 1967/1983; MacEachren and Ganter, 1990; Wood, 1993; Fisher, 1998; Cartwright *et al.*, 2001; Dodge *et al.*, 2008). The map user can adjust the mapped extent by folding it, bring it nearer to or farther from his or her eyes, annotate it using pens or coloured markers, and add pins to identify important locations (Wallace, 2011). Further, categories of map features can be added or removed from the map when decomposed into a set of overlapping transparent sheets, resulting in the common GIS interaction metaphor: the layer stack (McHarg, 1969; Goodchild, 2010). However, never has the possibility of interactivity been as impactful on the design, consumption, and overall utility of maps as it is today (Andrienko and Andrienko, 1999; Dykes, 2005; Harrower, 2008). Advances in personal computing and Internet technologies allow for instantaneous requests of new and unique map views, supporting the process of map-driven human reasoning in real time (MacEachren and Monmonier, 1992).

In the following, I accept a fundamental duality within Cartography between representation and interaction, while acknowledging their synergistic relationship (see Buja *et al.*, 1996, for a similar distinction between rendering and manipulation in Information Visualisation). ***Cartographic representation*** describes the graphics, sounds, haptics, etc., constituting a map that are employed to signify geographic information. The science of cartographic representation comprises more than 50 years of map-based research on

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perception (i.e., how maps are seen), cognition (i.e., how maps are understood), and semiotics (i.e., how maps become imbued with meaning) (MacEachren, 1995). One of the most significant theoretical breakthroughs regarding cartographic representation was the identification and articulation of the ***visual variables*** available to the cartographer when constructing a map, defined as the fundamental dimensions across which a representation can be varied to convey information. This is especially influential for representations that are visual (Bertin, 1967/1983; Morrison, 1974; Caivano, 1990; MacEachren, 1992), but also is an effective approach for conceptualizing and designing representations that are animated (DiBiase *et al.*, 1992), haptic (Griffin, 2002), or sonic (Krygier, 1994). These taxonomic frameworks provide a systematic way of varying representations when empirically examining which representations work the best. These empirical findings then can be used to answer the *how?* question of cartographic representation (i.e., the ***syntactics*** of the visual variables), assisting cartographers in the selection of representation choices appropriate for the given mapping context.

The other side of the duality is ***cartographic interaction***, defined formally as the dialogue between a human and a map mediated through a computing device (Roth, 2011); additional discussion about the definition of digital cartographic interaction is provided in the next subsection. Establishing a science of cartographic interaction is not an aspiration new to Cartography, with research on interactive maps dating at least to the 1960s (e.g., Pivar *et al.*, 1963; Engelbart and English, 1968); since 1990, there has been a series of edited volumes and special issues that directly engages with cartographic interaction, primarily in the context of Geovisualisation. One common research goal regarding interaction mirrored across most of these efforts—as well similar efforts in the related fields of Human—Computer Interaction, Information Visualisation, and Visual Analytics—is the identification and articulation of the fundamental components that constitute a cartographic interaction. In a research agenda for Geovisualisation, Cartwright *et al.* (2001, pp. 55, 57) state that ''A particularly difficult part of the problem is to develop a typology of geospatial interface tasks'' and go on to call for a ''typology of georepresentation operations'' for Geovisualisation. Similarly, Chi and Riedl (1998, p. 63) declare that ''Information Visualization has made great strides in development of a semiology of graphical representation methods, but lacks a framework for studying visualization operations'', suggesting that the logic that led to the visual variables in representation can and should be applied to interaction as well. Finally, Thomas *et al.* (2005, p. 76) include creation of a ''new science of interaction'' in their list of recommendations for the then nascent field of Visual Analytics, stating that ''The grand challenge of interaction is to develop a taxonomy to describe the design space of interaction techniques''. To avoid confusion across varying terminology, I use the term ***interaction primitives*** in the following to describe the fundamental kinds or types of interactions that altogether constitute an interaction exchange.

Here, I directly address this 'grand challenge of interaction' as it pertains to Cartography. Identification and articulation of cartographic interaction primitives is significant for at least three reasons: (1) they provide a consistent lexicon for describing competing interface designs and interaction strategies to the end of supporting classroom and workshop education on cartographic interaction as well as collaboration across teams of designers and developers engineering interactive maps; (2) they inform the design and analysis of scientific experiments, allowing for a systematic approach to the investigation of cartographic interaction both in terms of first scoping individual experiments and then aggregating research insights from these experiments into a single corpus; and (3) they inform the design and evaluation of interactive maps, answering the *how?* question of cartographic interaction (i.e., the syntactics of cartographic interaction primitives). It is important to note that there have been many efforts to address the topic of interaction primitives; there are literally dozens of existing approaches to parsing interaction into primitives offered in the fields of Cartography, Human–Computer Interaction, Information Visualisation, and Visual Analytics, as summarized below (e.g., Tables 1–3). The purpose of the following discussion is not to offer yet another taxonomy, but rather to take a critical step-back from the present suite of taxonomies in order to understand why scholars working on the same problem arrived at such diverse and at times contradictory taxonomical recommendations. Therefore, the primary contributions of this work are the organisation of extant interaction primitive taxonomies according to a broader conceptual framework and the subsequent synthesis of these taxonomies according to this framework. This presentation is offered from a cartographic perspective and is presented for use by cartographers, distinguishing itself from the relatively small number of efforts to summarize interaction in Human–Computer Interaction, Information Visualisation, and Visual Analytics (e.g., Pike *et al.*, 2009; Aigner, 2011); however, the scope of the review is purposefully broad to maintain relevance to these fields.

The paper proceeds with five additional sections. The next section provides a deeper discussion on the nature of cartographic interaction and the associated framework for conceptualizing cartographic interaction primitives. Specifically, Norman's (1988) stages of (inter)action model is modified to account for an interpretation of cartographic interaction as a two-way conversation between human and map, mediated by the digital computing platform. The third, fourth, and fifth sections provide a synthesis of extant taxonomies at three of these stages of interaction (operators, objectives and operands), revealing important concordances (overarching themes within each approach) and discordances (points of confusion) across the taxonomies within these stages. A summary and outlook are offered in the sixth and final section.

FRAMEWORK: NORMAN'S STAGES OF (INTER)ACTION MODEL

As introduced above, cartographic interaction is the dialogue between a human and a map mediated through a computing device (Roth, 2011). Such a definition acknowledges three components of a cartographic interaction that are necessary for the interaction to be completed digitally (Figure 1): (1)

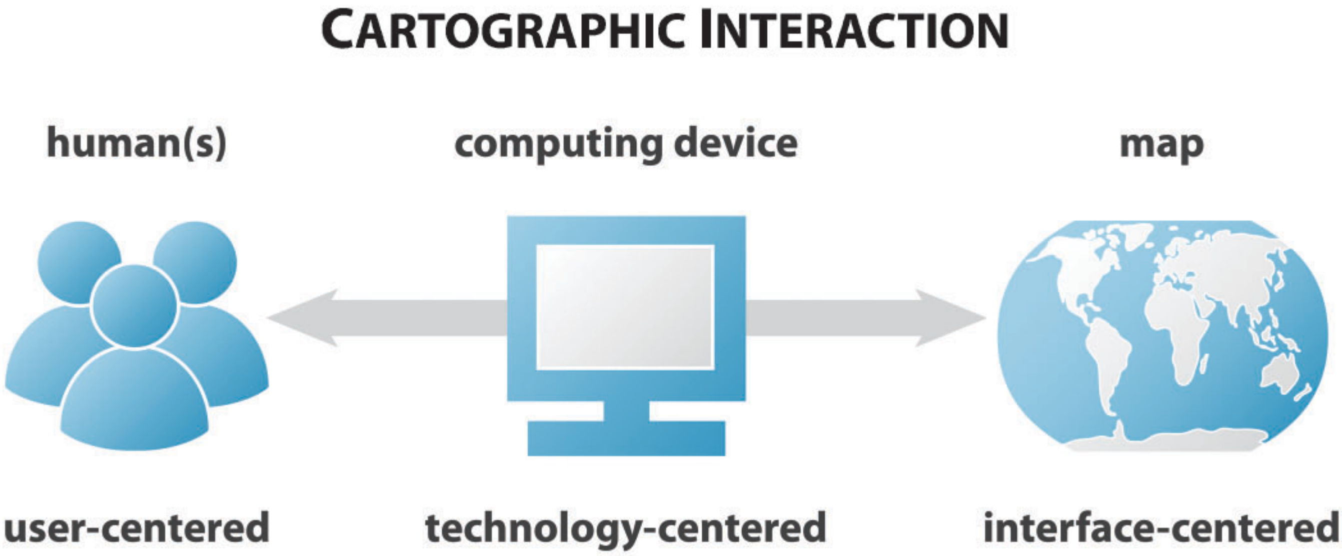

Figure 1. Components of Cartographic Interaction. Cartographic interaction is defined as the dialogue between a human (left) and a map (right) mediated through a computing device (middle). This gives rise to three areas of emphasis within a science of cartographic interaction: user-centred (left), interface-centred (right), and technology-centred (middle)

the human (leading to a user-centred perspective on cartographic interaction); (2) the map (leading to an interface-centred perspective on cartographic interaction); and (3) the computing device (leading to a technology-centred perspective on cartographic interaction). The human and map are agents in the interaction, holding the ability to affect change to the other. The human requests a new map view through the interface according to his or her goals, which evokes some kind of change to the map (i.e., the human poses a question). In turn, the updated map view is interpreted by the human, which evokes some kind of change to the human's mental schema regarding the mapped phenomenon, if new insights are discovered (i.e., if the map answers the question). If new insights are not discovered, the human may request a new map view in continued search of explanation, the map again will respond, and so on. A unique question and answer sequence between human and map completed as part of the conversation is described as an ***interaction exchange***, while the complete conversation is described as an ***interaction session*** (Edsall, 2003). The computing device is the mediator in this dialogue, affording the conversational exchanges to occur in real-time to support active discussion (MacEachren and Monmonier, 1992). A similar definition of interaction using a two-way dialogue or conversation metaphor is accepted in Human–Computer Interaction, Information Visualisation, and Visual Analytics (Yi *et al.*, 2007). Such a definition of cartographic interaction is not an attempt to renew the communication model in Cartography (which also is based on a dialogue or conversation metaphor, albeit one-way), but instead to acknowledge the mutual agency between human and map; see Roth (2011) for discussion on how the situated use and user context impact the cartographic interaction.

Most research on the design and use of interactive maps reported in the cartographic literature focuses not on cartographic interactions, but rather on ***cartographic interfaces***, described as the digital tools through which the interaction occurs. Such an interface-centred perspective, while an essential complement to the other perspectives, acknowledges only one of the three components of interaction (the map) and thus overlooks the human's motivation for seeking out a cartographic interface in the first place (a primary concern under a user-centred perspective). The cardinal distinction between interfaces and interactions is that humans *use* interfaces, but they *experience* interactions; it is the experience of the interaction that is meaningful, not the struggle to overcome the interface to foster this experience. Academics and professionals cartographers therefore must give equal attention (or shift emphasis completely) to ***interaction design*** (the careful decision making leading to a successful experience with an interactive map) as they do to ***interface design*** (the careful decision making leading to the successful use of an interactive map) (Beaudouin-Lafon, 2004). Best practices of cartographic interaction design promote effective visual storytelling in the context of Interactive Cartography (i.e., interactive maps for presentation of known insights, or visual stories; Eccles *et al.*, 2008) and effective visual thinking in the context of Geovisualisation (i.e., interactive maps for exploration to reveal insights into unknown anomalies, patterns, and trends; MacEachren, 1994).

Returning to the topic of interaction primitives, extant taxonomies differ according to the stage in the interaction exchange at which they offer primitives. There are a number of popular workflow models used in the field of Human–Computer Interaction to divide a single interaction exchange into a set of discrete stages (see Shneiderman and Plaisant, 2010, for a review). Theoretically, a taxonomy of cartographic interaction primitives can be formulated at any stage within a model; the set of cartographic primitives included in a taxonomy represents the complete solution space for a given stage of interaction. For example, Shneiderman (1996) offers a task-by-type taxonomy that acknowledges two stages of interaction, the first representing the user's objectives with the map (i.e., the tasks) and the second representing characteristics of the map with which the user is interacting

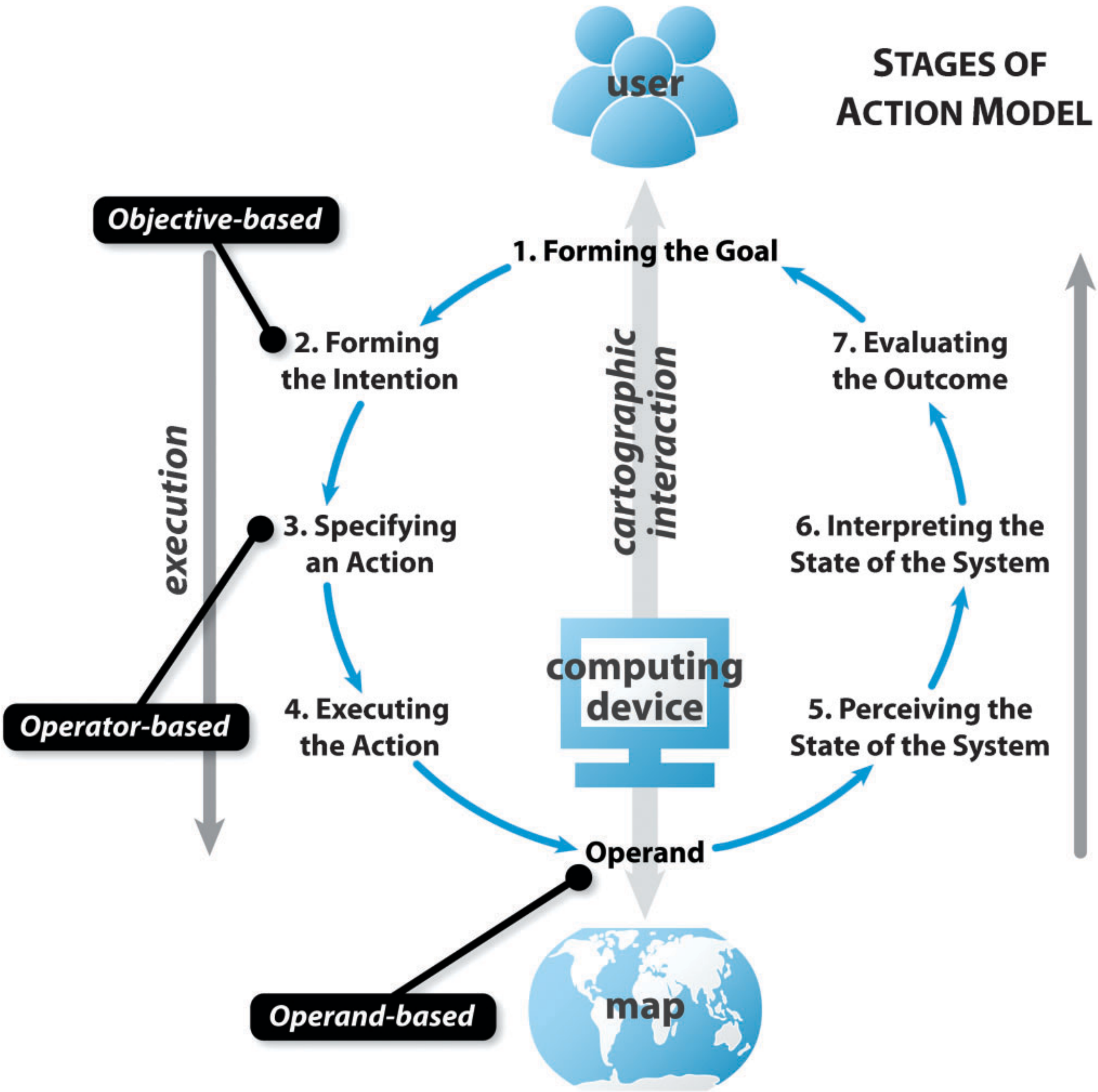

Figure 2. The Stages of Action Model and the Three O's of Cartographic Interaction. Norman (1988) decomposes a single execution–evaluation exchange into a sequence of seven stages. While a taxonomy of interaction primitives could be offered at all of these stages, there are three common approaches: (1) objective-based (at the stage of forming the intention); (2) operator-based (at the stage of specifying an action); and (3) operand-based (at the nexus of execution and evaluation, between the stages of executing an action and perceiving the state of the system). Figure 2 is placed in relation to the definition of cartographic interaction offered in Figure 1

that impact the interaction (i.e., the type). A limitation of most of these interaction workflow models is that they assume a one-way interaction exchange from user to representation, assigning agency to the human only.

One exception is Norman's (1988) stages of action model, offered as the conceptual foundation for a user-centred approach to the design of interactions between a human and an object (real or digital/virtual). Norman's stages of action model provides a useful framework for identifying possible cartographic interaction primitives within this two-way conversation metaphor, replacing the abstract question and answer sequence constituting an interaction exchange with a more concrete execution (i.e., the dialogue from the user to the map) and evaluation sequence (i.e., the dialogue from the map to the user). Further, Norman warns of two general kinds of failures in communication between humans and objects, described as gulfs that need to be overcome during interaction design: (1) the gulf of execution (i.e., a breakdown in the dialogue from the user to the map) and (2) the gulf of evaluation (i.e., a breakdown in the dialogue from the map to the user). In the model, Norman decomposes a single exchange in the overall interaction conversation into a sequence of seven observable steps, or ***stages of (inter)action***. Figure 2 shows these seven stages in relation to the definition of cartographic interaction depicted in Figure 1. These seven stages as applied for digital cartographic interaction include:

1. ***Forming the Goal***: The ***goal*** is what the user is trying to achieve and often is poorly defined and domain specific. In the context of cartographic interaction, goals motivate the use of geographic information and cartographic interfaces to this information. DiBiase's (1990) Swoopy diagram suggests one likely set of user goals that a cartographic interface may support: exploration, confirmation, synthesis, and presentation. Depending on the success or failure of past interactions, the goal itself either may evolve or remain static across the interaction session.
2. ***Forming the Intention***: The intention—referred to here as the ***objective*** to follow more closely with extant taxonomies of interaction primitives—describes the task that the user wishes to complete during the exchange. Objectives are formalized at an increased level of precision from the broader goals (e.g., a closed-ended task versus an open-ended task) and can be conceptualized as a statement of what the user wants to do with the cartographic interface. Objectives therefore form the cognitive user input for the cartographic interaction. The objective often is identified from past interaction sequences in the overall interaction session, particularly in the context of Geovisualisation in which the user may not have an objective in mind when beginning the interaction session (but does have a goal in mind: exploration).
3. ***Specifying an Action***: Specification of the action describes the translation from the user's objective formed in the prior stage to the functions provided by the cartographic interface that are perceived by the user to support this objective. These functions can be distilled into generic classes of ***operators***, or the actions provided through cartographic interfaces that allow for interactive change to the map display. The user becomes aware of the available operators through affordances built into the cartographic interface that indicate what the system can do and how it should be used. Operators rely upon one of five interface styles (direct manipulation, menu selection, form fill-in, command language, and natural language), but are more abstract than the interface styles that implement them, as the same operator can be implemented using any of these five interface styles (Howard and MacEachren, 1996).
4. ***Executing the Action***: Once the user identifies a possible operator for achieving an objective, he or she must execute that operator. ***Execution*** represents the 'doing' component of the interaction exchange, or the physical human input required to manipulate the provided cartographic interface through a pointing device (e.g., mouse, joystick, etc.), keying device (e.g., keyboard, keypad, etc.), or other mode (e.g., eye-tracking, speech recognition, gesture recognition). Most of the aforementioned interface styles require application of human motor skills to manipulate a physical input device; even map-based systems using speech-recognition typically are multi-modal and include motor movements such as pointing (e.g., MacEachren *et al.*, 2005). Computing devices provide the necessary logic to convert basic user inputs (i.e., raw input) into meaningful information that can be ingested by the application for manipulation of the display (i.e., semantic input). Thus, this potentially additional stage of interaction is offloaded from the user and onto the machine in the context of digital interactions.
5. ***Perceiving the State of the System***: The operator, once executed, manipulates the recipient of the operator in some way, changing the system state. The operator recipient, or ***operand***, describes the real or digital/virtual object with which the user is interacting either directly (through the direct manipulation interface style) or indirectly (through the other four interface styles) (Ward and Yang, 2003). For cartographic interactions, the operand is a digital map (or a component thereof) or other information graphic linked to the digital map. The operand is essential for completion of all seven stages of action, given the two-way conversation between user and map. However, the operand is particularly important directly following execution, as it is a primary way to provide feedback to the user, or signals about what happened as a result of the executed operator. It is through the provision of feedback about changes made to the operand that the map participates in the interaction conversation. Executing the Action (Figure 2, Stage #4) and Perceiving the State of the System (Figure 2, Stage #5) are the stages that emphasize the computing device through which the digital interaction is made possible (Figure 1: middle).
6. ***Interpreting the State of the System***: Once the updated operand is perceived, the user then must make sense of the update. One way to describe this stage is completion of the objective formulated in the second stage of action (Figure 2, Stage #2); once a new cartographic representation—or additional information about that cartographic representation—has been requested, it should be used to carry out the identified user objective. If the revised system state properly reflects application of the desired operator, completion of the objective may lead to the generation of new insight. In the context of the MacEachren and Ganter's (1990) pattern-matching model, Perceiving the State of the System (Figure 2, Stage #5) is similar to 'seeing-that', while Interpreting the State of the System (Figure 2, Stage #6) is similar to 'reasoning-why'.
7. ***Evaluating the Outcome***: The final evaluation compares the result of the operator with the expected or desired result. This includes both a critical evaluation of the validity of generated insights ('does this seem right?') and a meta-evaluation to determine if the overarching goal has been accomplished through generation of these insights ('do I have my answer?'). Following this evaluation, the user may initialize a new interaction exchange, restarting the seven stage sequence.

As stated above, it is theoretically possible to construct a taxonomy of interaction primitives at each of Norman's (1988) stages of interaction, producing a seven-dimensional taxonomy of interaction primitives (or eight-dimensional, when considering the operand as its own stage). Interestingly, extant taxonomical frameworks of interaction primitives align with one of only three stages, or include two of these three stages in a two-dimensional taxonomy, producing three recommended approaches to parsing exchanges into interaction primitives: (1) an objective-based approach (Figure 2, Stage #2); (2) an operator-based approach (Figure 2, Stage #3); and (3) an operand-based approach (Figure 2, the Map). These three approaches are described here as the ***three O's*** of cartographic interaction. Extant objective-based, operator-based, and operand-based taxonomies of interaction primitives are synthesized in the subsequent sections. Each section includes a table summary of extant taxonomies offered at the given stage as well as a concept map showing the relationships of extant taxonomies (line connections) and the relative frequencies of interaction primitives (text size). Only a minimal attempt was made to disambiguate the terms in each concept map figure in order to provide an unfiltered view of the terminology currently in use; areas of overlap or confusion instead are discussed in the following synthesis sections. Italics are used to differentiate terms used to describe an interaction primitive from regular uses of the same terms.

OBJECTIVE-BASED TAXONOMIES

Objective-based approaches compartmentalize interaction at the Forming the Intention stage (Figure 2, Stage #2), emphasizing the kinds of tasks the user may wish to complete with the cartographic interface. Objective-based taxonomies often are described as task ontologies; the development of functional task ontologies has been identified as a key research need for Geovisualisation specifically (e.g., Fabrikant, 2001; Andrienko *et al.*, 2003) as well as GIScience more broadly (e.g., Goodchild, 1988; Albrecht, 1997). Table 1 summarizes extant objective-based taxonomies from the domains of Cartography, Human–Computer Interaction, Information Visualisation, and Visual Analytics, which include: Wehrend and colleagues (1990, 1993), Zhou and Feiner (1998), Blok *et al.* (1999), MacEachren *et al.* (1999), Crampton (2002), Andrienko *et al.* (2003), Amar *et al.* (2005), and Yi *et al.* (2007). The Figure 3 concept map indicates the similarities and differences across objective-based taxonomies and the relative frequencies of each interaction primitive.

It is possible to segment the Figure 3 concept map into three general subsections based on their overlap, delineated in the figure by dashed lines. At the top of the graphic, there is a concentrated set of equivalent objective-based taxonomies that include only the primitives *identify* and *compare*: Wehrend and Lewis's (1993) 'operations', Blok *et al.*'s (1999) 'exploratory tasks', and Andrienko *et al.*'s (2003) 'cognitive operations'. The definitions of *identify* and *compare* are largely consistent across taxonomies; *identify* describes the examination of a single map object, while *compare* extends *identify* to consider similarities and differences across multiple map objects. The MacEachren *et al.*'s (1999) 'meta-operations' also are included in this subsection of the Figure 3 concept map, but extends the two-part objective-based taxonomies with the primitive *interpret*. Drawing from previous work on map reading in Cartography by Muehrcke (1986), MacEachren *et al.* (1999) define *interpret* as determining the relationship of an identified feature to a real-world entity (an important objective when considering the triadic model of semiotics).

The second subsection in the concept map, located in the middle of Figure 3, includes two objective-based taxonomies that extend the simpler taxonomies including only *identify* and *compare*: Wehrend's (1993) 'visualization goals' and Zhou and Feiner's (1998) 'visual tasks'. Wehrend proposes nine 'visualization goals', defined as

Table 1. Extant objective-based taxonomies of interaction primitives

Author(s)	Title	Objectives
Wehrend and Lewis (1990)	Operations	(1) identify, (2) compare
Wehrend (1993)	Visualisation Goals	(1) identify, (2) locate, (3) distinguish, (4) categorize, (5) cluster, (6) rank, (7) compare, (8) associate, (9) correlate
Zhou and Feiner (1998)	Visual Tasks	(1) associate, (2) background, (3) categorize, (4) cluster, (5) compare, (6) correlate, (7) distinguish, (8) emphasize, (9) generalize, (10) identify, (11) locate, (12) rank, (13) reveal, (14) switch, and (15) encode
Blok *et al.* (1999)	Exploratory Tasks	(1) identify, (2) compare
MacEachren *et al.* (1999)	Meta-operations	(1) identify, (2) compare, (3) interpret
Crampton (2002)	Interactivity Tasks	(1) examine, (2) compare, (3) (re)order/(re)sort, (4) extract/suppress, (5) cause/effect
Andrienko *et al.* (2003)	Cognitive Operations	(1) identify, (2) compare
Amar *et al.* (2005)	Analytic Tasks	(1) retrieve value, (2) filter, (3) compute derived value, (4) find extremum, (5) sort, (6) determine range, (7) characterize distribution, (8) find anomalies, (9) cluster, (10) correlate
Yi *et al.* (2007)	User Intents	(1) select, (2) explore, (3) reconfigure, (4) encode, (5) abstract/elaborate, (6) filter, (7) connect

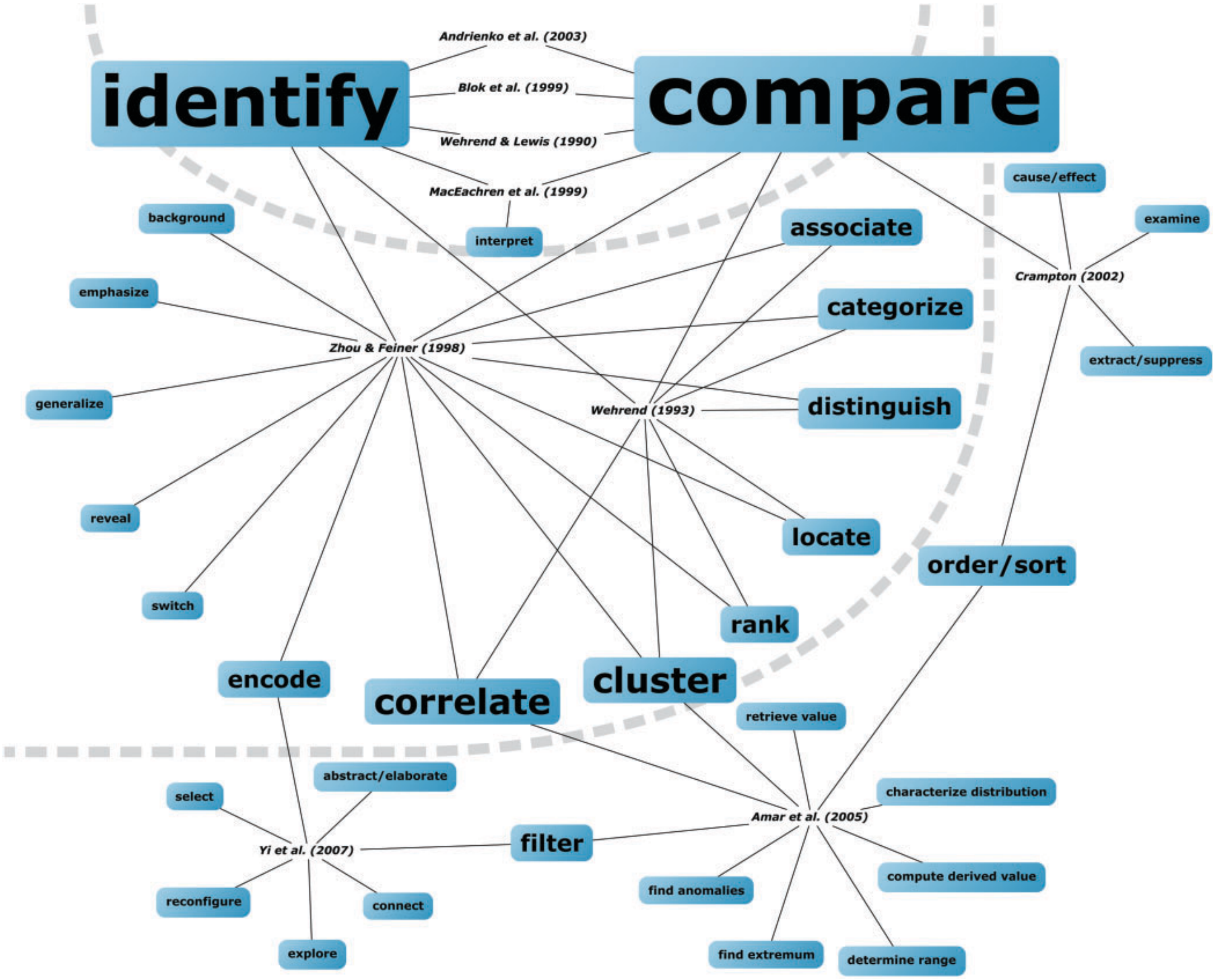

Figure 3. A concept map of objective-based primitives. The concept map shows the relationships among extant objective-based taxonomies and the relative frequency of the included interaction primitives. The objective-based concept map can be segmented into three subsections based on relations: a concentrated set of simple taxonomies that include the primitives *identify* and *compare* (top); two taxonomies that expand upon the *compare* primitive (middle); unprecedented or orthogonal taxonomies that have minimal overlap with others (outer rim)

actions that a user would like to perform on his or her information. Visualisation goals include: (1) *identify* (establish the characteristics by which an object is distinctly recognisable), (2) *locate* (determine the position of an object in absolute or relative terms), (3) *distinguish* (recognize one object as different from another or group of others), (4) *categorize* (place objects into a set of divisions for organisation), (5) *cluster* (join objects into groups based on similar characteristics—this task differs from *categorize* in that clustering creates the groups as the objects are placed in them, rather than using an *a priori* set of intervals), (6) *rank* (give an object an order or position with respect to other objects of the same type), (7) *compare* (notice similarities and differences between/among objects when they have no explicit ranking), (8) *associate* (link or join two or more objects in a relationship), and (9) *correlate* (establish a direct connection between/among objects). There are two characteristics of Wehrend's taxonomy worth noting. First, Wehrend chooses to separate *locate* from *identify*; *locate* is a task with a clear spatial emphasis, but is not found in any of the other objective-based taxonomies within the literature, cartographic or otherwise. Using this distinction, the *identify* primitive narrowly focuses upon the attributes of a particular map feature that already has, or needs to be, *located* on the map. Albrecht (1997) describes this difference as *thematic search* versus *spatial search* in the context of GIS operators. Second, Wehrend includes a large number of primitives that go beyond *compare* to organize individual information elements at different strengths; examples that may be considered special cases of *compare* include *associate*, *categorize*, *cluster*, *correlate*, *distinguish*, and *rank*.

Zhou and Feiner (1998) directly extend Wehrend's (1993) nine-part taxonomy to generate a total of 15 'visual tasks', defined as abstract visualisation techniques that can be accomplished through a set of low-level operations. Added primitives include: (10) *background*, (11) *emphasize*,

(12) *reveal*, (13) *generalize*, (14) *switch,* and (15) *encode*; definitions are not offered for the added six primitives. A further extension made by Zhou and Feiner is organisation of the taxonomy around the objective's visual accomplishment and visual implication. The ***visual accomplishment*** describes the change to the operand as a result of completing an objective, provided to the user through a feedback mechanism. In contrast, the ***visual implication*** describes the new objectives that can be achieved after first completing a given objective, indicating a conditioning that may occur when considering multiple interaction exchanges together, or multiple loops through the stages of interaction model during an interaction session (Figure 2).

The final subsection located along the outer rim of the Figure 3 concept map includes largely unprecedented or orthogonal offerings that exhibit minimal overlap with taxonomies in the other Figure 3 subsections, or with each other. These taxonomies include Crampton's (2002) 'five interactivity tasks', Amar *et al.*'s (2005) 'analytic tasks', and Yi *et al.*'s (2007) 'user intents'. One explanation for this disconnect is that at least one interaction primitive (and often more) in each of the remaining objective-based taxonomies is better understood as an operator. Despite this blending of objectives and operators, the Crampton, Amar *et al.* and Yi *et al.* taxonomies are considered objective-based because of the scholars' overall focus on user intentions, rather than the interfaces provided to accomplish such intentions. Each remaining objective-based taxonomy is treated separately in the following due to the divergence in their approaches.

Crampton (2002) offers five 'interactivity tasks', defined as the kinds of actions users conduct with a cartographic interface. Interactivity tasks include: (1) *examine* (looking at and inspecting a feature), (2) *compare* (examining two or more displays at once), (3) *(re)order/(re)sort* (examining the information in addition to performing a direct manipulation on them), (4) *extract/suppress* (highlighting and filtering), and (5) *cause/effect* (linking views to identify the strength and nature of a relationship across representations). This taxonomy is important because it is organized across a characteristic of the user objectives: their level of ***sophistication***, or amount and complexity of the subsequent operators required to complete the objective. Sophistication increases in an ordinal manner across the five objectives, from *examine* to *cause/effect*. The least sophisticated primitives are those also found in the simpler objective-based taxonomies (e.g., Wehrend and Lewis, 1990; Blok *et al.*, 1999; Andrienko *et al.*, 2003), including the common *compare* as well as *examine*, a primitive that overlaps with *identify*. The objectives at an intermediate level of sophistication are confused with operators, describing manipulations to the operand such as a request for new visual structure (*(re)order/(re)sort*) or a request to show a subset of features (*extract/suppress*). Although *(re)order* and *(re)sort* conceptually are similar to Wehrend's (1993) *rank* and *categorize* respectively—and thus may be representative of objectives—the definition of *(re)order/(re)sort* provided by Crampton focuses specifically on manipulation to the view through a cartographic interface. The most sophisticated objective primitive, *cause/effect*, describes a specific case of *compare* in which the goal is to establish a one-way temporal relationship between compared items. As described above, Wehrend's objective-based taxonomy also includes additional discrimination within the *compare* primitive, although does not include *cause/effect*.

Amar *et al.* (2005) list 10 'analytic tasks' in the context of Information Visualisation. This taxonomy is interesting because it is empirically derived, unlike all previously mentioned objective-based taxonomies (and most extant taxonomies of interaction primitives generally). Amar *et al.* asked college students in an Information Visualisation course to generate a listing of possible objectives that could be accomplished with an example information set using commercial visualisation tools. These objectives then were grouped using the affinity diagramming method, revealing 10 analytic tasks: (1) *retrieve value* (find attributes about an identified information case), (2) *filter* (find cases whose attributes meet a set of conditions), (3) *compute derived value* (calculate an aggregate representation for a set of cases), (4) *find extremum* (identify cases with extreme values), (5) *sort* (rank cases according to a numeric attribute), (6) *determine range* (find the span of attributes for a set of cases), (7) *characterize distribution* (produce statistics that characterize the distribution of a set of cases), (8) *find anomalies* (identify cases that do not match a given relationship or expectation), (9) *cluster* (group cases based on similar attributes), and (10) *correlate* (identify relationships across cases by their attributes). Interestingly, *identify* and *compare* are not listed and instead are replaced with more specific terminology common to statistics, such as *compute derived value*, *find anomalies*, *find extremum,* and *retrieve value* for the *identify* primitive and *characterize distribution*, *cluster, correlate, determine range,* and *sort* for the *compare* primitive. This replacement perhaps is appropriate if a more detailed delineation within *identify* and *compare* is possible and/or necessary; other objective-based taxonomies that include both the generic *identify* and *compare* primitives, along with special cases of these primitives, insufficiently redefine what is meant by *identify* and *compare*, resulting in an objective-based taxonomy that is not mutually exclusive. Finally, the primitive *filter* is included in the Amar *et al.* and subsequent Yi *et al.* (2007) taxonomies, but aligns more closely with operator-based taxonomies.

Yi *et al.* (2007) identify seven 'user intents' (i.e., objectives) that drive the application of interaction techniques (i.e., operators). Like Amar *et al.* (2005), Yi *et al.* used an affinity diagramming approach to develop the taxonomy, although on secondary sources rather than empirical evidence. Their review included 59 papers and 51 visualisation systems, producing a collective total of 331 interaction techniques. Techniques were grouped by seven user intents: (1) *select* (mark a case of interest), (2) *explore* (display a different subset of cases), (3) *reconfigure* (change the arrangement of cases), (4) *encode* (change the method of representing the information), (5) *abstract/elaborate* (show the information in more or less detail), (6) *filter* (show cases that satisfy a set of conditions), and (7) *connect* (highlight associated or related items). When examining the definitions alone, it is possible that all primitives within this objective-based taxonomy are better considered as generic descriptions or characteristics of operators. Most operator-based taxonomies within Cartography collapse what Yi *et al.*

call *explore* and *filter* into a single operator primitive, using only the term *filter* and instead reserving the term *explore* for use as an overarching goal, not an objective (DiBiase, 1990; MacEachren, 1994). Yi *et al.* do not include *identify*, with *select* representing the conceptually most similar included primitive (i.e., a combination of the *identify* objective with an operator that then marks the identified map feature). Interestingly, Yi *et al.* explicitly reject inclusion of *compare*, the most pervasive objective primitive, arguing that it is a higher level goal that builds upon other interaction primitives. Thus, they do not agree with Crampton's (2002) notion of sophistication, instead arguing for a taxonomy of primitives that are at the same semantic level of meaning, or same level of sophistication.

Before concluding the summary on objective-based taxonomies, it is important to note that there are a considerable number of ***purpose-driven*** objective-based taxonomies in the Human–Computer Interaction and Usability Engineering literature that are specific to a single application domain and include highly detailed descriptions of the primitives. Construction of purpose-driven objective-based taxonomies is part of the task analysis or work domain analysis step in a user-centred approach to design and development of a cartographic interface (Robinson *et al.*, 2005). This stage of the user-centred workflow can be streamlined with a broadly applicable and generally accepted objective-based taxonomy in place *a priori*, as the designers and developers simply can work through the objective primitives to determine which need to be supported, to generate specific examples of each included objective primitive, and to brainstorm potential operators that support the identified objectives. One such example within Cartography is presented by Auer (2009), who describes a robust 'task typology' of spatiotemporal dynamic map reading tasks specific to the study of bird distribution and migration patterns; his final, purpose-driven objective-based taxonomy was constructed through the integration of the existing objective-based taxonomies from Wehrend (1993), Blok (2000), and Andrienko *et al.* (2003) and user input from a focus group session with expert ornithologists.

OPERATOR-BASED TAXONOMIES

Operator-based approaches compartmentalize interaction at the Specifying the Action stage (Figure 2, Stage #3), focusing upon the cartographic interfaces that make manipulation of the representation possible. At this stage of interaction, the user identifies the operator he or she believes will support the objective, but does not execute the operator itself using available input devices. The cartographic interface designer must ensure that the provided set of operators completely supports the user's objectives and that the user is aware of the available operators through strong affordances. Table 2 summarizes extant operator-based taxonomies, which include: Becker and Cleveland (1987), Shepherd (1995), Buja *et al.* (1996), Chuah and Roth (1996), Shneiderman (1996), Dykes (1997; drawing directly from Shepherd, 1995), Dix and Ellis (1998), MacEachren *et al.* (1999), Masters and Edsall (2000; drawing directly from MacEachren *et al.*, 1999), Keim (2002), Ward and Yang (2003), and Edsall *et al.* (2008). The Figure 4 concept map indicates the similarities and differences across operator-based taxonomies and the relative frequencies of each interaction primitive.

Unlike the concepts maps in Figure 3 and Figure 5, the Figure 4 concept map cannot be segmented easily into subsections of similar structures because of a much greater amount of lexical variation across the operator-based taxonomies. These taxonomies commonly employ the same term to refer to different operators or employ different terms that refer to the same operator. This results in a complex concept map with only several primitives common to multiple operator-based taxonomies and many primitives found in only one or two taxonomies. The Figure 4 concept map instead is segmented according to the frequency of the primitives across taxonomies. The following review is organized by this delineation, first treating the small subset of primitives common to a large portion of the operator-based taxonomies (*brushing*, *focusing*, and *linking*), but often used in an inconsistent or contradicting manner, and then treating the menagerie of remaining primitives that together exhibit several common themes (e.g., operators that manipulate the symbolisation in the cartographic representation, operators that manipulate the user's viewpoint on the cartographic representation, and enabling operators).

The central subsection of the Figure 4 concept map includes three primitives found in a large portion of the reviewed objective-based taxonomies: *brushing*, *focusing*, and *linking*. *Brushing*, one of the earliest digital interaction operators offered in the Exploratory Data Analysis literature, is the only primitive common to a majority of the reviewed objective-based taxonomies. Becker and Cleveland (1987) describe *brushing* as a highly interactive technique for directly selecting groups of information items in a display, making it one of the few offered operator primitives specific to one interface style: direct manipulation. While several scholars suggest that brushing is possible through other interface styles, these alternatives are not considered because they either require direct manipulation of linked interface widgets (which acts as either *brushing* of that widget or *filtering* of a linked control) (e.g., Ward, 1997) or are non-interactive (e.g., Monmonier, 1989). Becker and Cleveland identify four 'brushing operations': (1) *highlight* (brushing changes the representation of the selected items; this operator is further delimited by Robinson, 2006, 2011), (2) *shadow highlight* (brushing changes the unselected items), (3) *delete* (brushing deletes the selected items), and (4) *label* (brushing retrieves the labels for selected items). Thus, under the Becker and Cleveland conceptualisation, brushing is an enabling interaction that indicates the map elements (i.e., the operands) to receive some additional treatment (i.e., a second operator); additional work on brushing operations is provided in Becker *et al.* (1987).

It perhaps is this dual-step nature of *brushing* that has caused confusion in subsequent uses of the term in operator-based taxonomies, with several scholars emphasizing the initial, selection step in their definition of the

Table 2. Extant operator-based taxonomies of interaction primitives

Author(s)	Title	Operators
Becker and Cleveland (1987)	Brushing Operations	(1) highlight, (2) shadow highlight, (3) delete, (4) label
Shepherd (1995)	Observer-related Behaviour	(1) observer motion, (2) object rotation, (3) dynamic comparison, (4) dynamic re-expression, (5) brushing
Buja *et al.* (1996)	Interactive View Manipulations	(1) focusing, (2) linking, (3) arranging views
Chuah and Roth (1996)	Basic Visualisation Interaction Operators	(1) encode data (graphic), (2) set-graphical-value (graphic), (3) manipulate objects (graphic), (4) create (set), (5) delete (set), (6) summarize (set), (7) join (set), (8) add (data), (9) delete (data), (10) summarize (data), (11) join (data)
Shneiderman (1996)	Tasks	(1) overview, (2) zoom, (3) filter, (4) details-on-demand, (5) relate, (6) history, (7) extract
Dykes (1997)	Observer-related Behaviour	(1) observer motion, (2) object rotation, (3) dynamic comparison, (4) dynamic re-expression, (5) brushing
Dix and Ellis (1998)	Kinds of Interaction	(1) highlight and focus, (2) accessing extra information, (3) overview and context, (4) same representation-changing parameters, (5) same data-changing representation, (6) linking representations
MacEachren *et al.* (1999)	Interaction Forms	(1) assignment, (2) brushing, (3) focusing, (4) colourmap manipulation, (5) viewpoint manipulation, (6) sequencing
Masters and Edsall (2000)	Interaction Modes	(1) assignment, (2) brushing, (3) focusing, (4) colourmap manipulation, (5) viewpoint manipulation, (6) sequencing
Keim (2002)	Interaction and Distortion Techniques	(1) dynamic projection, (2) filtering, (3) zooming, (4) distortion, (5) linking and brushing
Ward and Yang (2003)	Interaction Operators	(1) navigation, (2) selection, (3) distortion
Edsall *et al.* (2008)	Interaction Forms	(1) zooming, (2) panning/re-centring, (3) re-projecting, (4) accessing exact data, (5) focusing, (6) altering representation type, (7) altering symbolisation, (8) posing queries, (9) toggling visibility, (10) brushing and linking, (11) conditioning

brushing primitive and others emphasizing the secondary, transformation step, or one of Becker and Cleveland's (1987) four 'brushing operations'. Shepherd (1995) and Dykes (1997) focus on the former step, defining *brushing* as an information selection technique, a use that is synonymous with Ward and Yang's (2003) *selection* primitive. It is necessary to be critical of the *brushing*-as-*selection* interpretation, as it equates *brushing* with direct manipulation, making it an interface style rather than a unique operator. Conversely, MacEachren *et al.* (1999) and Masters and Edsall (2000) focus on the secondary stage of *brushing* in their definition of the primitive, particularly emphasizing a visual change that is applied once a subset of elements have been selected, or Becker and Cleveland's *highlight* and *shadow highlight*. Interestingly, three of the taxonomies explicitly conflate *brushing* with one of the other three commonly found operators, collapsing them into a single primitive. Keim (2002) and Edsall *et al.* (2008) conflate their use of *brushing* with *linking* (defined below), defining *brushing* as a selection operator that visually relates across multiple, coordinated views. Dix and Ellis (1998) conflate *brushing* with *focusing* (defined below), which implies an emphasis on Becker and Cleveland's *delete* operation; however, their subsequent discussion of the primitive is much closer to the definition provided by Keim and Edsall *et al.* Finally, Becker and Cleveland's *label* primitive is related to Shneiderman's (1996) *details-on-demand*, Dix and Ellis's *accessing extra information*, and Edsall *et al.*'s *accessing exact information*.

The second and third common primitives in Figure 4, *focusing* and *linking*, originate from the Buja *et al.* (1996) operator-based taxonomy presented in the context of coordinated, multi-view visualisation, or a class of interactive systems that allow the user to create multiple representations of the same information set, with the operators performed upon one representation permutated to all others (Roberts, 2008). Buja *et al.* discuss three types of 'interactive view manipulations' that support coordinated, multi-view visualisation: (1) *focusing* individual views (any operation that changes the detail of a subset of objects), (2) *linking* multiple views (posing a query graphically and then having all views update with the result), and (3) *arranging* multiple views (adjusting the order or position of a large number of views). These three manipulations then are paired by Buja *et al.* with three objectives (*finding Gestalt*, *posing queries*, and *making comparisons*, respectively), producing a simple objective-by-operator taxonomy. The primitives *focusing*, and *linking* are defined inconsistently in subsequent taxonomies, while the third primitive *arranging views* is similar to Persson *et al.*'s (2006) *arranging many views* (a taxonomy included with the treatment of operands, given its overall focus) and Yi

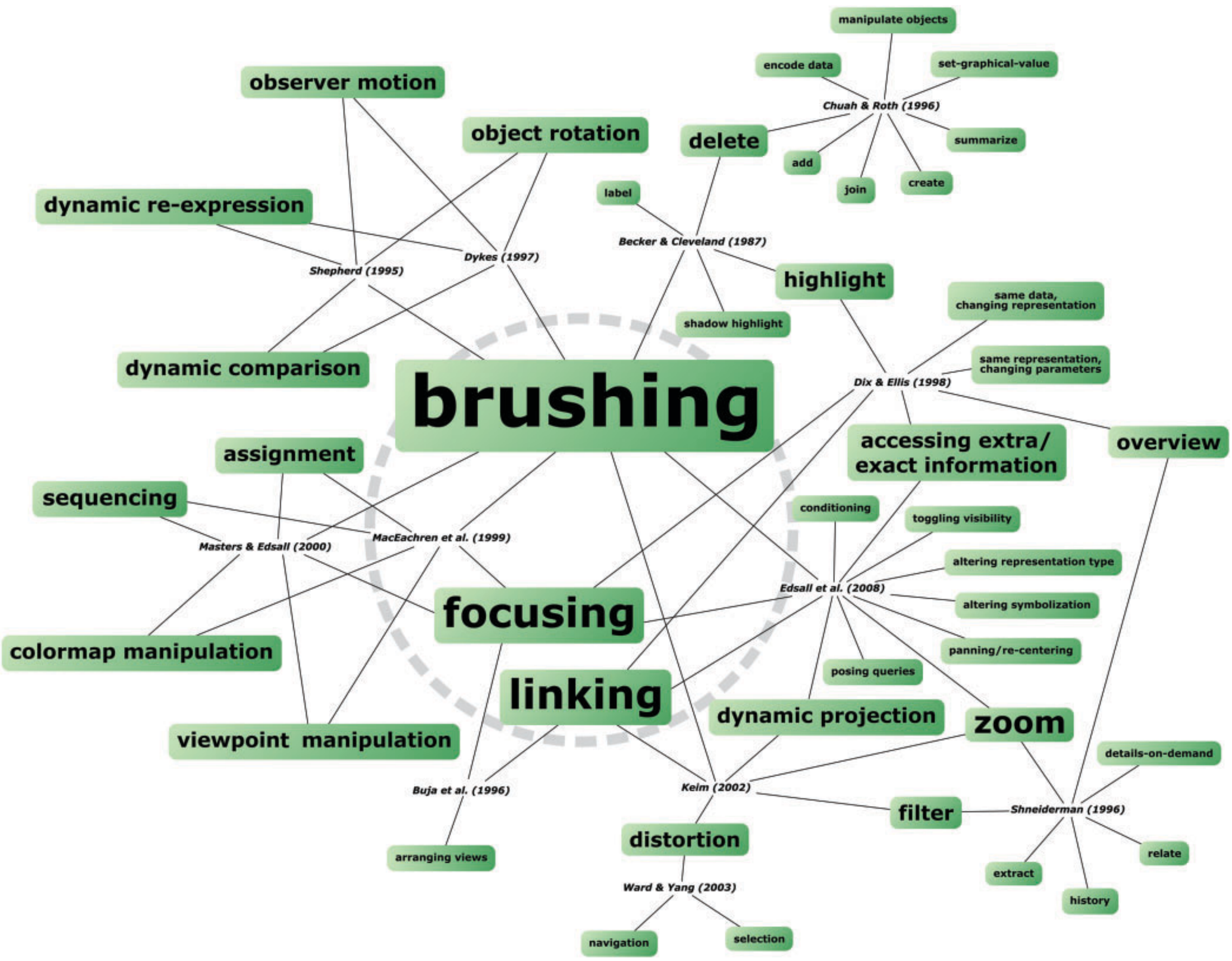

Figure 4. A concept map of operator-based primitives. The concept map shows the relationships among extant operator-based taxonomies and the relative frequency of the included interaction primitives. The operator-based concept map can be segmented into two subsections based on relations: commonly included primitives with inconsistent or contradicting definitions (centre); primitives included in only one or two taxonomies, but that altogether exhibit several common themes (outer rim)

et al.'s (2007) *reconfigure* (a taxonomy included with the above treatment of objectives).

The primitive *focusing* is used in three different ways by subsequent scholars. Buja *et al.* (1996) emphasize the increase or decrease in detail in the displayed data elements. Edsall *et al.* (2008, p. 9) follow this definition, equating *focusing* to an action of "data zooming", which itself is synonymous with Shneiderman's and Keim's definitions of *zoom*. In contrast, MacEachren *et al.* (1999) and Masters and Edsall (2000) define *focusing* as a technique for limiting the inclusion of information elements to those meeting user-defined conditions, a definition that is synonymous with Shneiderman's and Keim's definition of *filter* and Edsall *et al.*'s definition of *conditioning*. Finally, Dix and Ellis (1998) conflate *brushing* and *focusing*, which restricts application of *focusing* to the direct manipulation interface style; this use of *focusing* is similar to Edsall *et al.*'s *posing queries* primitive.

Most definitions of the *linking* primitive do not qualify it as an operator. Given the emphasis on coordinated, multi-view visualisation, Buja *et al.*'s (1996) definition of *linking* itself is conceptually similar to Cleveland and Becker's (1987) *brushing* when the interaction is applied to coordinated views; as noted above, Keim (2002) and Edsall *et al.* (2008) follow this conflation of *brushing* and *linking*. Such a perspective on *brushing* makes it a three-step action: (1) identification of items of interest through *selection*; (2) manipulation of the selected items through an interaction operator; and (3) coordination of this interaction operator to other views through *linking*. MacEachren *et al.* (1999, p. 323) are clear not to include this form of *linking* as an interaction operator, instead considering it a characteristic of the 'representation forms'. Thus, perhaps only the second component of this three-step *brushing*+operator+*linking* action represents a true manipulation to the display, meaning that *brushing* and *linking* in isolation do not qualify as interaction operators. Interestingly, Dix and Ellis (1998) offer an alternative definition of *linking* in which the user requests successive representations for sequential display. Such a definition is similar to Shepherd's (1995) *dynamic comparison* primitive

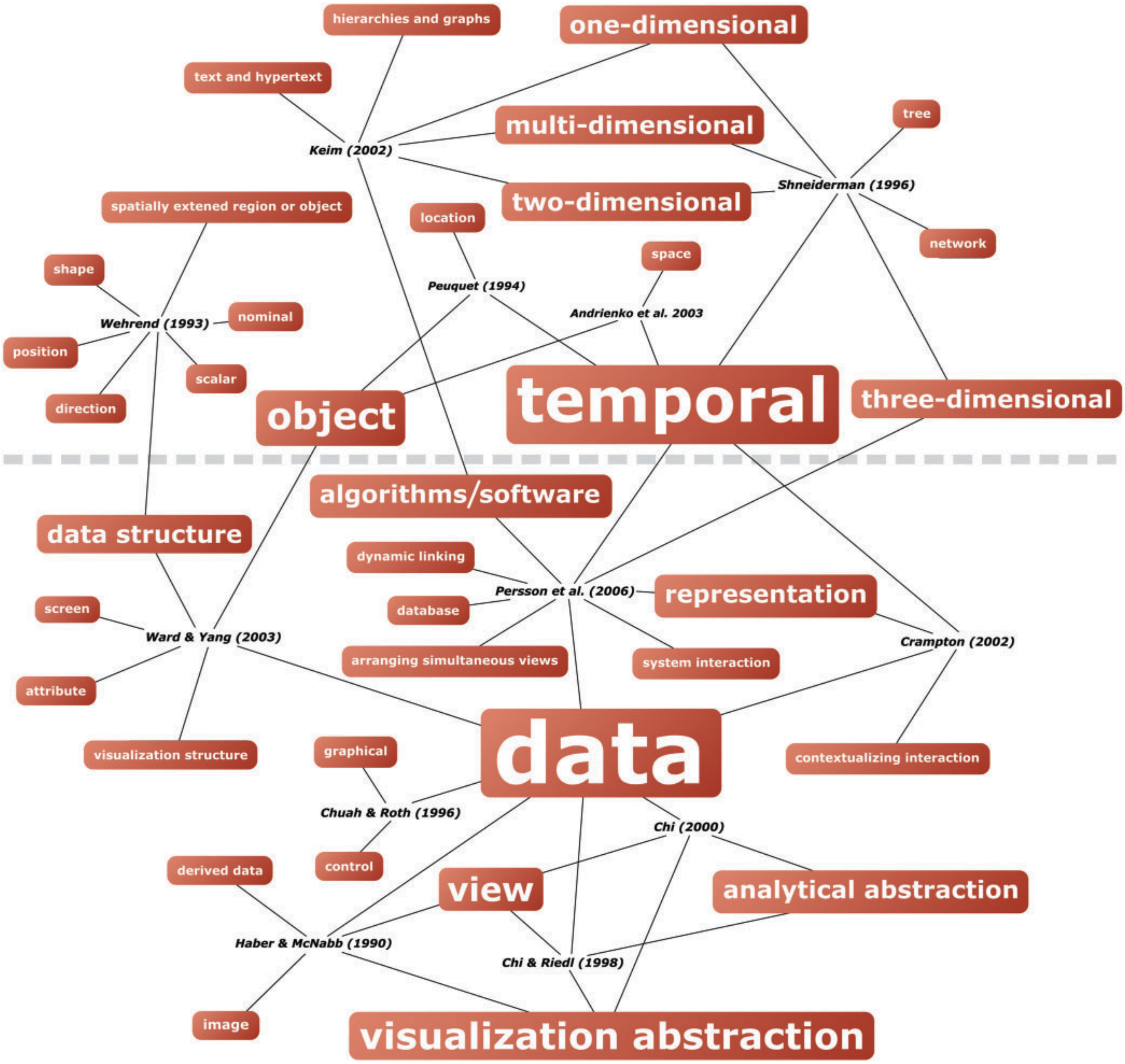

Figure 5. A concept map of operand-based primitives. The concept map shows the relationships among extant operand-based taxonomies and the relative frequency of the included interaction primitives. The operand-based concept map can be segmented into two subsections based on relations: type-centric (top) and state-centric (bottom)

and MacEachren *et al.*'s (1999) and Masters and Edsall's (2000) *sequencing* primitive, which both describe generation of a series of related representations for display, as side-by-side small multiples, atop one another in the same representation, or as a cartographic animation. This kind of manipulation does qualify as an interaction operator and may be extended to the *linking* of individual information items (such as during the synthesis stage of science) or the coordinated linking of views indicated by the user through an enabling interaction (Hardisty, 2003).

The outer rim of Figure 4 includes a large number of primitives included in only one or two of the extant operator-based taxonomies. Despite the range of terminology used, these less frequent primitives align with one of three general themes: (1) operators that manipulate the symbolisation in the cartographic representation; (2) operators that manipulate the user's viewpoint of the cartographic representation; and (3) enabling interaction operators. Each category of operators is reviewed next.

The first theme includes operators that manipulate the symbolisation included in the cartographic representation beyond what would be included in *highlight* (i.e., a temporary symbol change to indicate features of interest). The first set of primitives aligning with this theme adjust the included map layers (in the context of reference mapping) or the mapped variable(s) (in the context of thematic mapping); Edsall *et al.*'s (2008) *toggle visibility* primitive describes the former situation and MacEachren *et al.*'s (1999) and Masters and Edsall's (2000) *assignment* primitive describes the latter. Keim's (2002) *dynamic projection* is similar to assignment, but also includes the number of axes to which variables can be assigned (e.g., in a self-organizing map representation); Edsall *et al.*'s *re-projection* extends *dynamic projection* to include changes to the map projection as well. The second set of primitives aligning with this theme adjust the kind of cartographic representation displayed without changing what is mapped (e.g., a change from a choropleth map to a proportional symbol map), producing a new representation of the same information; this operator primitive is described as *altering representation type* by Edsall *et al. dynamic re-expression* by Shepherd (1995) and Dykes (1997) (a term first introduced by Tukey, 1977), *encode data* by Chuah and Roth (1996), and *same data, changing representation* by Dix and Ellis (1998). A final set of primitives aligning with this theme adjust the symbolisation parameters (e.g., classification scheme, colour scheme) without changing the representation type or the underlying data; this operator primitive is described as *altering symbolisation* by Edsall *et al. colourmap manipulation* by MacEachren *et al.* and Master and Edsall *same representation, changing parameters* by Dix and Ellis, and *set-graphical-value* by Chuah and Roth.

The second theme cutting across these peripheral primitives includes operators that manipulate the user's viewpoint. This theme covers primitives considered as part of map browsing (Harrower and Sheesley, 2005), which includes changes to the extent of the map (i.e., *pan*) and changes to the scale of the map (i.e., *zoom*). The combination of these manipulations are described as *observer motion* by Shepherd (1995) and Dykes (1997), as *viewpoint manipulation* by MacEachren *et al.* (1999) and Masters and Edsall (2000), and *navigation* by Ward and Yang (2003). Edsall *et al.* (2008) maintain the two components of map browsing as individual primitives, using the terms *panning/re-centring* and *zooming*, respectively. *Zooming* is fundamental to Shneiderman's (1996) visual information seeking mantra, which combines *zoom* and the aforementioned *filter* to move from an overview of the information space to specific details. However, the use of *zoom* for map browsing, common within Interactive Cartography, is different from Shneiderman's use of *zoom* in that it indicates a change in map scale only, and not necessarily a change in the detail of the displayed map features. The term ***semantic zoom*** instead is used within Cartography to describe a change in the abstraction of the cartographic representation when changing scales (Tanaka and Ichikawa, 1988). Inversely, Ward and Yang (2003) and Keim (2002) use the primitive *distortion* to describe a change in the detail while maintaining an overview or the surrounding context (i.e., without changing the scale of the entire map). Finally, MacEachren *et al.* and Masters and Edsall include the notion of rotation in their definition of *viewpoint manipulation* when applied in the context of 2.5D or 3D representations, such as virtual globes; Shepherd and Dykes reserve this as the separate primitive *object rotation*, while Edsall *et al.* include it as part of their *re-projecting* primitive.

The final theme includes ***enabling interactions***, or operators required to prepare for, or clean up from, operators that perform work (Whitefield *et al.*, 1993; Davies, 1998). The Chuah and Roth (1996) operator-based taxonomy emphasizes enabling operators, including the primitives *add*, *create*, *delete*, *join*, and *manipulate objects*. The selection step of *brushing* may be best conceptualized as an enabling operator, if included as a primitive by itself. The entire set of primitives related to map browsing also may be considered as enabling operators, as they are applied to overcome constraints in screen real-estate (Haklay and Zafiri, 2008). Although primarily an objective-based taxonomy, Yi *et al.* (2007) reserve a special primitive that includes *system interactions* such as undo and redo. Other ostensibly enabling operators include Shneiderman's (1996) primitives *extract* (save a sub-collection of items plus the querying parameters for future use outside of the application) and *history* (undo or redo an operation using the interaction history), which are both examples of an enabling interaction performed to clean up from past work.

As with objective-based taxonomies, there is a subset of purpose-driven operator-based taxonomies that are specific to Cartography. These taxonomies were developed for qualitative data analysis of ***interaction logs***, or a document listing every user interaction operator employed during an experiment or real-world interaction session, along with a timestamp. Cartographic interaction experiments that construct a purpose-driven operator-based taxonomy for qualitative data analysis include MacEachren *et al.* (1998), Andrienko *et al.* (2002), Edsall (2003), and Robinson (2008a, b).

OPERAND-BASED TAXONOMIES

Finally, ***operand-based approaches*** compartmentalize interaction at the nexus of Norman's (1988) execution and evaluation, between the stages of Executing an Action (Figure 2, Stage #4) and Perceiving the State of the System (Figure 2, Stage #5). Here, the focus is on the operand, or the digital/virtual object with which the user is interacting. The user interface designer must ensure that proper feedback is provided to the user about how the operand has changed as a result of the executed operator. Table 3 summarizes extant operand-based taxonomies, which include: Haber and McNabb (1990), Wehrend (1993), Peuquet (1994), Chuah and Roth (1996), Shneiderman (1996), Chi and colleagues (1998, 2000), Crampton (2002), Keim (2002), Andrienko *et al.* (2003), Ward and Yang (2003), and Persson *et al.* (2006). The Figure 5 concept map indicates the similarities and differences across operand-based taxonomies and the relative frequencies of each interaction primitive.

It is possible to segment the Figure 5 concept map into two subsections that represent very different avenues to identifying and articulating operand primitives: type-centric and state-centric. These sections are delineated by a horizontal dashed line through the middle of Figure 5.

Table 3. Extant operand-based taxonomies of interaction primitives

Author(s)	Title	Operands
Haber and McNabb (1990)	Data States	(1) data, (2) derived data, (3) visualisation abstraction, (4) view
Wehrend (1993)	Types of Data	(1) scalar, (2) nominal, (3) direction, (4) shape, (5) position, (6) spatially extended region or object, (7) structure
Peuquet (1994)	TRIAD framework	(1) location, (2) time, (3) object
Chuah and Roth (1996)	Output State	(1) graphical, (2) data, (3) control
Shneiderman (1996)	Data Types	(1) one-dimensional, (2) two-dimensional, (3) three-dimensional, (4) temporal, (5) multi-dimensional, (6) tree, (7) network
Chi and Riedl (1998)	Data States	(1) data, (2) analytical abstraction, (3) visualisation abstraction, (4) view
Chi (2000)	Data States	(1) data, (2) analytical abstraction, (3) visualisation abstraction, (4) view
Crampton (2002)	Interactivity Types	(1) data, (2) representation, (3) temporal dimension, (4) contextualizing interaction
Keim (2002)	Data Types	(1) one-dimensional, (2) two-dimensional, (3) multi-dimensional, (4) text and hypertext, (5) hierarchies and graphs, (6) algorithms and software
Andrienko *et al.* (2003)	Components of Spatiotemporal Data	(1) space, (2) time, (3) objects
Ward and Yang (2003)	Interaction Operands and Spaces	(1) screen, (2) data, (3) data structure, (4) attribute, (5) object, (6) visualisation structure
Persson *et al.* (2006)	Interaction Types	(1) representation, (2) algorithms for the creation of a representation, (3) database, (4) arranging simultaneous views, (5) dynamic linking, (6) temporal dimension, (7) three-dimensional, (8) system interaction

Type-centric operator-based taxonomies (Figure 5: top) discriminate primitives according to characteristics of the represented information. In contrast, ***state-centric*** operand-based taxonomies (Figure 5: bottom) emphasize the linear workflow from raw data through onscreen rendering, a sequence of computational transformations referred to as the information visualisation pipeline (Card *et al.*, 1999); operand primitives are discriminated according to the state in this pipeline at which the user is interacting. Both avenues are reviewed in the following section.

Beginning with type-centric operand-based taxonomies located in the top half of Figure 5, Wehrend (1993) offers an early set of seven 'types of data' with which a user can interact. Data type primitives include: (1) *scalar* (a quantity specified by one number), (2) *nominal* (a property specified qualitatively), (3) *direction* (a position to which motion or another position is relative), (4) *shape* (the outline or surface of a feature), (5) *position* (the location of a point in space), (6) *spatially extended region or object* (the location of an area in space), and (7) *structure* (an arrangement of multiple objects into a single hierarchy or network). Although there is little overlap with this taxonomy and subsequent type-centric operand-based taxonomies, Wehrend did set a precedent in combining a type-centric operand-based taxonomy with an objective-based taxonomy, producing a two-dimensional objective-by-operand taxonomy (i.e., task-by-type taxonomy) to prescribe the appropriate visual representation based upon the objective and operand context.

Shneiderman (1996) and Keim (2002) each present a type-centric set of operand primitives as part of their own task-by-type taxonomies, with the pair of type-centric taxonomies exhibiting much overlap; there are no common information type primitives between the above Wehrend (1993) taxonomy and the Shneiderman and Keim taxonomies. Shneiderman lists seven 'data types': (1) *one-dimensional* (linear information, defined primarily as textual information rather than Wehrend's, 1993, numerical *scalar*), (2) *two-dimensional* (geospatial information), (3) *three-dimensional* (defined as 'real world' objects, with the third dimension representing vertical spatial position, not an attribute), (4) *temporal* (information collected over time, which differ from *one-dimensional* information in that they have a start and end date and individual elements may overlap), (5) *multi-dimensional* (numerous attributes for each information element), (6) *tree* (a hierarchical variant of Wehrend's *structure*), and (7) *network* (an unordered variant of Wehrend's *structure*). Keim offers a similar listing of six 'data types', although there are several notable differences from Shneiderman: (1) *one-dimensional* (defined as information with a temporal dimension, matching Shneiderman's *temporal* rather than Shneiderman's *one-dimensional*), (2) *two-dimensional* (as defined by Shneiderman), (3) *multi-dimensional* (as defined by Shneiderman), (4) *text and hypertext* (as defined as Shneiderman's *one-dimensional* primitive), (5) *hierarchies and graphs* (treating Shneiderman's *tree* and *network* types as a single primitive, equating to Wehrend's *structure*), and

(6) *algorithms and software* (a special case of Shneiderman's *one-dimensional*, separated from the more basic *text and hypertext* primitive). A key similarity in the Shneiderman and Keim type-centric operand-based taxonomies is that they both describe geographic information, and associated cartographic representations, using the primitive *two-dimensional*; Shneiderman reserves the primitive *three-dimensional* for geographic depictions such as virtual globes as well as non-geographic 3D representations. Thus, the information type primitive largely is fixed in the context of cartographic interaction, reducing the utility of a task-by-type, or objective-by-operand, taxonomy for Cartography.

One type-centric operand distinction that is influential in the context of Interactive Cartography and Geovisualisation is provided by Andrienko *et al.* (2003, p. 510), who offer an 'operational task taxonomy' to characterize the full suite of tasks that a user may need to complete with a spatiotemporal cartographic interface. The Andrienko *et al.* operational task taxonomy includes three dimensions across which map use tasks vary: (1) cognitive operation (the visual analytic process applied to the representation), (2) search target (the component of the spatiotemporal information under investigation), and (3) search level (the percentage of all map features under consideration). The cognitive operation dimension is synonymous with the concept of an interaction objective (not an operator, using the terminology introduced in this paper); as summarized above, Andrienko *et al.* only include *identify* and *compare* as objective primitives (an expanded treatment for the operational task taxonomy is provided in Andrienko and Andrienko, 2006). The search target dimension effectively is a simplification of the Shneiderman (1996) and Keim (2002) type-centric operand-based taxonomies that emphasize the spatial and temporal components of information. Drawing on Peuquet's (1994) TRIAD framework for conceptualizing spatiotemporal information, Andrienko *et al.*, identify three search targets: (1) *space* (the 'where', which is synonymous with the *two-dimensional* primitive described by Shneiderman and Keim), (2) *time* (the 'when', which is synonymous with the *temporal* primitive described by Shneiderman, and the *one-dimensional* primitive described Keim), and (3) *objects* (the 'what' or 'who', which describes the attributes of the spatiotemporal phenomenon). The Andrienko *et al.* type-centric operand-based taxonomy is important for interactions that are explicitly cartographic, as the *space* primitive is kept under consideration at all times; the *space* primitive is either known *a priori*, acting as a constraint during interaction with the *time* and/or *object* operand primitives, or is the unknown operand primitive under investigation, with the *temporal* and/or *object* primitives acting as the constraints during interaction. The third dimension, the search level, simplifies Bertin's (1967/1983) concept of levels of map reading to include two primary search levels: *elementary* (reading and interaction with only one map feature) versus *general* (reading and interaction with several-to-all map features); Bertin's intermediate level is removed from the Andrienko *et al.*'s framework to make the problem tractable, as they viewed its difference from the general level as conceptually minor.

The bottom half of Figure 5 spans state-centric operand-based taxonomies, which discriminate operand primitives according to the information visualisation pipeline, or the transformations and rendering techniques applied to the information, rather than characteristics of this information itself. Haber and McNabb (1990) present an early visualisation pipeline, described as the 'visualisation process', which includes four state-centric primitives: (1) *data* (the raw data, particular to the output of simulations in the Haber and McNabb taxonomy), (2) *derived data* (usable abstractions of the raw data, or information), (3) *abstract visualisation* (information that has been translated for representation), and (4) the displayable *image* (the representation itself). The user is able to interact with any of these four state-centric primitives, as well as interactively request a transition between states through three operators: (1) *data enrichment/enhancement* (transition from data to derived data), (2) *visualisation mapping* (transition from derived data to the abstract visualisation), and (3) *rendering* (transformation from the abstract visualisation to the view). The Haber and McNabb operand-based taxonomy illustrates the difference between type-centric and state-centric operand-based taxonomies: in the aforementioned type-centric taxonomies, primitives are defined as characteristics of the mapped information, which then prescribe the proper representation form, whereas in the state-centric taxonomies, both the information and the representation (and any abstraction in between) are primitives themselves, or points in the computational transformation from data through information to representation at which the user may interact.

Several subsequent scholars offer conceptual variants to the Haber and McNabb (1990) state-centric operand-based taxonomy. Chi and colleagues (1998, 2000) present a similar operand-based taxonomy, using slightly different terminology for the same four state-centric primitives: (1) *data*, (2) *analytical abstraction*, (3) *visualisation abstraction*, and (4) *view*. Chuah and Roth (1996) simplify the Haber and McNabb pipeline into two state-centric primitives (*data state* and *graphical state*), but add a third *control state* primitive to include enabling interactions with the system, such as accessing permissions and undoing past interactions.

Ward and Yang (2003) present a state-centric operand-based taxonomy of 'interaction spaces', defined as the conceptual object on which the interaction operator is applied. As with the state-based taxonomies described by Haber and McNabb (1990), Chuah and Roth (1996), and Chi and colleagues (1998, 2000), this taxonomy focuses primarily on the difference between data interaction and information/graphic interaction, although it includes several additional divisions within both. Interaction spaces include: (1) *screen–space* (interaction with screen pixels and not the data itself), (2) *data value–space* (interaction with multivariate data values), (3) *data structure–space* (interaction with components of data organisation), (4) *attribute–space* (interaction with graphical widgets to adjust the visualisation by attribute), (5) *object–space* (interaction on a 3D object onto which the visualisation is projected), and (6) *visualisation structure–space* (interaction on the labels and axes of the visualisation). Ward and Yang pair these interaction spaces with three interaction operators (*navigation*, *selection,* or *distortion*), producing a state-based operator-by-operand taxonomy.

One interpretation of the state-centric perspective is an overall emphasis on the technological challenges in moving from the stage of Executing an Action (Figure 2, Stage #4) to the stage of Perceiving the State of the System (Figure 2, Stage #5), in contrast to the type-centric perspective that instead emphasizes characteristics of the operand itself (Figure 2, the Map); this difference is analogous to the difference between the technology-centred (Figure 1: middle) and interface-centred perspectives (Figure 1: right) on cartographic interaction. As discussed in Roth (2011), the technology-centred view—while essential for implementing a useful and usable cartographic interface—is less appropriate as a subject of scientific inquiry; the great dynamism of interactive mapping technologies means that scholarly contributions from a technology-centred perspective exhibit an abbreviated shelf-life and offer little opportunity for extension.

Aside from the Andrienko *et al.* (2003) type-centric operand-based taxonomy, the previously reviewed set of operand-based taxonomies are derived from sources outside of the Cartography. Interestingly, two additional operand-based taxonomies within the cartographic literature blend type-based and state-based approaches; each is marked in the following. Crampton (2002) describes four broad-level 'interactivity types': (1) *interaction with the data* (state primitive), (2) *interaction with the data representation* (state primitive), (3) *interaction with the temporal dimension* (type primitive), and (4) *contextualizing interaction* (similar to the *control state* primitive included in Chuah and Roth, 1996). In contrast, Persson *et al.* (2006) describe eight broad-level 'interaction types': (1) *interaction with the representation model* (state primitive), (2) *interaction with the algorithms for the creation of a representation* (state primitive), (3) *interaction with the primary model/database query* (state primitive), (4) *arranging many simultaneous views* (included under the *control state* in Chuah and Roth, 1996), (5) *dynamic linking with further display types* (this appears to be more of an operator distinction than an operand distinction), (6) *interaction with the temporal dimension* (type primitive), (7) *interaction with the 3D visualisation* (type primitive), and (8) *system interaction* (similar to the *control state* in Chuah and Roth, 1996).

CONCLUSION: CONCORDANCES, DISCORDANCES AND OUTLOOK

This paper contributes to the 'grand challenge' of cartographic interaction: identification and articulation of the fundamental interaction primitives (Thomas *et al.*, 2005, p. 76). Taking a perspective on cartographic interaction that accepts a two-way dialogue or conversation metaphor (Figure 1), Norman's (1988) stages of action model was applied to divide a single interaction exchange into seven observable steps (eight, if considering the map to be its own stage). With the stages of interaction framework in place, it then was possible to compare and contrast extant taxonomies according to the stage at which they were offered, allowing for a critical examination of the current solution space for the aforementioned 'grand challenge'. One key insight into the 'grand challenge' revealed that the otherwise disparate taxonomies aligned with one of three stages of interaction (or a two of these three stages in the case of objective-by-operator, objective-by-operand, and operator-by-operand taxonomies). These three approaches to parsing interaction were characterized as objective-based taxonomies (Figure 3), operator-based taxonomies (Figure 4), and operand-based taxonomies (Figure 5). Once sorted and synthesized, it was possible to determine overarching themes within each approach (concordances) as well as common points of confusion (discordances).

Important concordances and discordances regarding extant objective-based taxonomies of interaction primitives include:

- The *identify* and *compare* primitives are the most commonly included across the reviewed objective-based taxonomies (Wehrend and Lewis, 1990; Wehrend, 1993; Zhou and Feiner, 1998; Blok *et al.*, 1999; MacEachren *et al.*, 1999; Andrienko *et al.*, 2003).
- The more complex objective-based taxonomies commonly discriminate within the *compare* primitive (Wehrend, 1993; Zhou and Feiner, 1998; Crampton, 2002; Amar *et al.*, 2005) and less frequently discriminate within the *identify* primitive (Amar *et al.*, 2005).
- Of those taxonomies that do discriminate within the *identify* and *compare* primitives, only Amar *et al.* (2005) removes the broader *identify* and *compare* to ensure that the objective-based taxonomy is mutually exclusive.
- Several scholars organize the primitives into categories (e.g., visual accomplishments and visual implications from Zhou and Feiner, 1998) or across a continuum (e.g., level of sophistication from Crampton, 2002), while others explicitly argue against inclusion of operators at different semantic levels of meaning (Yi *et al.*, 2007).
- The distinction between objectives and operators described in Figure 2 is not considered by many authors, resulting in several taxonomies offered at an intermediate stage or a blending of the two stages (e.g., Zhou and Feiner, 1998; Crampton, 2002; Amar *et al.*, 2005; Yi *et al.*, 2007).

Important concordances and discordances regarding extant operator-based taxonomies of interaction primitives include:

- *Brushing* is the only primitive found in a majority of the reviewed operator-based taxonomies (Becker and Cleveland, 1987; Shepherd, 1995; Dykes, 1997; MacEachren *et al.*, 1999; Masters and Edsall, 2000; Keim, 2002; Edsall *et al.*, 2008), with *focusing* (Buja *et al.*, 1996; Dix and Ellis, 1998; MacEachren *et al.*, 1999; Masters and Edsall, 2000; Edsall *et al.*, 2008) and *linking* (Buja *et al.*, 1996; Dix and Ellis, 1998; Keim, 2002; Edsall *et al.*, 2008) also found in many operator-based taxonomies (although not in a majority).
- The *brushing* primitive is at least a two-step action composed of a *selection* step and a subsequent manipulation step (e.g., *highlight*, *shadow highlight*, *delete*, *label*); scholars following Becker and Cleveland (1987) incorrectly emphasize only one or the other in their definition.

- The *focusing* primitive has been defined in three ways: (1) *focusing* as providing more detail (Buja *et al*., 1996; Edsall *et al*., 2008); (2) *focusing* as synonymous with *filtering* (MacEachren *et al*., 1999; Masters and Edsall, 2000); and (3) *focusing* as the secondary action combined with *brushing* (Dix and Ellis, 1998).
- Most definitions of the *linking* primitive do not qualify it as an operator (e.g., Buja *et al*., 1996; Keim, 2002; Edsall *et al*., 2008), instead making it the third step constituting *brushing*.
- There is a large group of primitives that manipulate the symbolisation included in a cartographic representation, including those for altering the map information that is symbolized (*assignment*, *dynamic projection*, *re-projecting*, *and toggle visibility*), those for altering the type of cartographic representation that is displayed (*altering representation type*, *dynamic re-expression*, *encode data*, and *same data-changing representation*), and those for altering the graphic parameters of the cartographic representation (*altering symbolisation*, *colourmap manipulation*, *same representation-changing parameters*, and *set-graphical-value*).
- There is a large group of primitives that manipulate the user's viewpoint to the cartographic representation, including *distortion*, *navigation*, *observer motion*, *object rotation*, *panning/re-centre*, *re-projecting*, *viewpoint manipulation,* and *zooming*.
- Many of the primitives included in operator-based taxonomies represent enabling interactions.

Finally, important concordances and discordances regarding extant operand-based taxonomies of interaction primitives include:

- There are two avenues for identifying and articulating operand primitives: type-centric (Wehrend, 1993; Peuquet, 1994; Shneiderman, 1996; Keim, 2002; Andrienko *et al*., 2003) and state-centric (Haber and McNabb, 1990; Chuah and Roth, 1996; Chi and Riedl, 1998; Chi, 2000; Ward and Yang, 2003).
- Type-centric operand-based taxonomies often are paired with objective-based taxonomies to construct an objective-by-operand (task-by-type) taxonomy (Wehrend, 1993; Shneiderman, 1996; Keim, 2002); Ward and Yang (2003) provide the only example of a state-centric objective-by-operand taxonomy.
- The type-centric taxonomies offered by Shneiderman (1996) and Keim (2002) place geographic information under the *two-dimensional* primitive, which in turn limits the utility of these taxonomies for understanding interactions that are explicitly cartographic (although they remain useful in the context of coordinated, multi-view visualisation).
- Andrienko *et al.* (2003) present a useful operational task typology that includes three dimensions: (1) cognitive operation (the visual analytic process applied to the representation, or the operator), (2) search target (the component of the spatiotemporal information under investigation), and (3) search level (the percentage of all map features under consideration).
- State-centric operand-based taxonomies are based on the visualisation pipeline (Card *et al*., 1999) and separate interactions with the raw data from interactions with the representation.

So, where do we go from here? The above framework and synthesis offer a contemporary snapshot of extant efforts to construct a taxonomy of interaction primitives, and the concordances and discordances therein. However, construction of a taxonomy is not considered the 'grand challenge of interaction' because it is the endpoint of a line of research. Rather, such a taxonomy affords the opportunity to seek answers to the diverse and evolving set of questions that the science of cartographic interaction approaches; it is an *enabling* structure. As an outlook, it is necessary to look forward to several of the core questions facing the science of cartographic interaction in the near future, and to make the connection explicit on how the above framework and synthesis directly support investigation of these core questions:

1. ***A consistent lexicon for education and practice:*** A primary purpose of a taxonomy of cartographic interaction primitives is the provision of a consistent lexicon for describing map-based interaction strategies and interface designs. A consistent lexicon is equally important for supporting classroom and workshop education as it is for supporting collaboration across teams of designers and developers engineering interactive maps (and for making a painless transition from the classroom to the work station). As stated in the introduction, the purpose of the research reported here was not to contribute an additional taxonomy of interaction primitives, but instead to seek structure in the corpus of extant taxonomies; rather than a dictionary providing a comprehensive set of definitions, the above synthesis generated a look-up table providing a complex set of translations. With a deeper understanding of the nature of cartographic interaction primitives in place, however, it is now possible to derive theoretically a composite taxonomy based on the framework. Further, it is now possible to design a series of studies eliciting knowledge from interactive map designers and developers in order to determine which portions of extant taxonomies are ecologically valid and generally logical, and which are not. Initial work taking a blended theoretical-empirical approach to establishing a composite taxonomy is provided by Amar *et al.* (2005), Yi *et al.* (2007), and Roth (2012). Despite the need for a consistent lexicon, it is important to note that any composite taxonomy must remain malleable to changes in technologies, as the solution space for cartographic interaction, and therefore, the primitives themselves, are likely to expand with time.
2. ***A theoretical apparatus for science:*** Establishing a composite taxonomy with a consistent lexicon allows for design of a series of experiments that investigate the nature of cartographic interaction. Such a theoretical apparatus derived from the framework supports both the scoping of individual cartographic interaction experiments and subsequent aggregation of results into a unified corpus. However, even purpose-driven taxonomies (e.g., Auer, 2009) developed around a unique problem improve the ability to systematize cartographic

interaction experiments; the framework then affords follow-up interpretation and integration with other experiments. While the above synthesis is purposefully broad in scope, future work applying the framework for cartographic interactions should investigate explicitly how spatial interactions are special. As discussed in the operand-based approaches, *space* (or the *two-dimensional* and *three-dimensional*) is but one type-centric operand primitive in a larger set (Andrienko *et al*., 2003). It is important to reveal how the unique characteristics of spatial and geographic information—such as scale, topology, and spatial autocorrelation—both impose constraints on cartographic interaction and afford opportunities in cartographic interface design. The work of Anselin and colleagues (e.g., 1989, 1999, 2006), Dykes and colleagues (e.g., 1995, 2003, 2007), and Unwin and colleagues (e.g., 1994, 1998, 2003) provide important insight into the nature of spatial interactions from the perspective of Exploratory Spatial Data Analysis. Despite the emphasis on the *space* operand primitive, it is important to remind that a science of cartographic interaction should address the gamut of operand primitives, as there is great potential (and much existing work) in representing the other operand primitives using *space* for context (map-based tag clouds, map animations, network maps/linear cartograms, etc.).

3. ***Interactive map design and use guidelines:*** The ultimate purpose of the framework, and the science of cartographic interaction broadly, is the generation of interactive map design and use guidelines that positively impact cartographic interaction practice. As stated in the introduction, there have been many such breakthroughs regarding the science of cartographic representation, with development of a syntactics of visual variables among the most significant. Such an integrated theoretical-empirical approach in turn may offer the same bounty of insight regarding cartographic interaction that the visual variables have provided for cartographic representation, ultimately resulting in a syntactics of cartographic interaction primitives that prescribe the design and use of interactive maps (i.e., the *how?* question of cartographic interaction). There currently exist in the cartographic literature a large number of reports on individual interactive maps or map-based applications, emphasizing novel cartographic interface solutions. Moving forward, we should go beyond the simple reporting of these new designs and additionally provide evidence as to why they work through administration of interaction experiments informed by the framework. Initial work towards generating interactive map design and use guidelines through interaction experiments include MacEachren *et al.* (1998), Andrienko *et al.* (2002), Edsall (2003), Robinson (2008a, b), and Roth (2011).

The framework and synthesis provided above act as a foundation on which to approach these research questions, but there remains a great amount of work to be done regarding the science of cartographic interaction. The unanswered research questions posed above are but a subset of those for which a science of cartographic interaction currently has no answer and eventually will need to answer. I therefore encourage others to embrace the fundamental duality between representation and interaction in Cartography and join in the effort to make sense of cartographic interaction.

BIOGRAPHICAL NOTES

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