Human-Centered Interactivity of Visualization Tools: Micro- and Macro-level Considerations

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Abstract Visualization tools can support and enhance the performance of complex cognitive activities such as sense making, problem solving, and analytical reasoning. To do so effectively, however, a human-centered approach to their design and evaluation is required. One way to make visualization tools human-centered is to make them interactive. Although interaction allows a user to adjust the features of the tool to suit his or her cognitive and contextual needs, it is the quality of interaction that largely determines how well complex cognitive activities are supported. In this chapter, interactivity is conceptualized as the quality of interaction. As interactivity is a broad and complex construct, we categorize it into two levels: micro and macro. Interactivity at the micro level emerges from the structural elements of individual interactions. Interactivity at the macro level emerges from the combination, sequencing, and aggregate properties and relationships of interactions as a user performs an activity. Twelve micro-level interactivity elements and five macro-level interactivity factors are identified and characterized. The framework presented in this chapter can provide some structure and facilitate a systematic approach to design and evaluation of interactivity in human-centered visualization tools.

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1 Introduction

A human-centered approach to visualization requires the consideration of a number of issues, including the perceptual and cognitive characteristics of users, their goals and needs, and the nature of human tasks and activities. One way to make visualization tools (VTs) human-centered is to design them with interactive features, so that users can engage in a dialogue with a VT through a back-and-forth flow of information. In this manner, users can adjust visualizations to suit their needs and preferences. Although it is widely acknowledged that making VTs interactive enhances their utility, the degree of utility depends upon the quality of the interaction with a VT.

Numerous contextual and ideological factors have influenced the manner in which the use of interactive technologies has been studied. For instance, Crystal and Ellington [13] discuss how task analysis in human-computer interaction research has its historical roots in early studies of physical activity, organizational management, and human factors. These influences led to a system-centric approach when characterizing interaction with technologies. Paul Dourish [14] describes the influence of computational models of the mind on early HCI research, and how the result was wide adoption of procedural accounts of human activity. Consequently, such models largely informed the conceptualization and design of interactive technologies. These views, however, have been challenged by recent research in cognitive science, which posits that cognitive activity is distributed, embodied, and generally far richer and more complex than previous models suggest. In addition, much research in the past involving human activity has overlooked complexity in order to make objects of study 'researchable' [17]. Such approaches have only limited utility, and although potentially useful as analytic frameworks, cannot adequately characterize human cognitive activity.

In addition to these shifting views, interactive technologies are nowadays being used to engage in more complex activities than the simple structured tasks of the early days of HCI [2, 3, 22, 28, 47, 53, 56]. More recently, researchers in various domains related to human-centered visualization and informatics (e.g., [3, 17, 28, 45]) have begun to focus more on the needs, characteristics, and activities of users. Technological advances in recent years have led to the development of highly interactive visualization tools that are used to engage in complex and unstructured activities. For instance, visualization tools are being used to support sense making of large and complex social networks, solving open-ended problems in science, and making decisions regarding global distribution of resources. While researchers now understand what leads to effective visualizations for simple and well-defined tasks, we still know very little about the dynamics of effective VTs for complex activities [22, 53].

Part of the challenge of designing effective VTs is the lack of comprehensive frameworks to inform the conceptualization and discussion of interactivity. Researchers investigating different aspects of human-centered informatics have recently been emphasizing the need for theoretical frameworks. For instance, Kaptelinin and Nardi [28] have proposed that there is currently "marked interest in frameworks that can provide an explanation of why and how certain subjective phenomena are taking place in situations surrounding the use of interactive technologies". A number of other researchers have identified the lack of theoretical frameworks as a major research problem in information visualization, human-computer interaction, visual analytics, and other related areas over the past decade (see [16, 27, 29, 42, 54, 57, 68]).

Frameworks that thoroughly and methodically characterize interactivity in VTs can greatly assist designers and evaluators. Presently, there is no common vocabulary for discussing the interactivity of VTs, and frameworks can provide such a vocabulary. This chapter makes a contribution to address this need, and is part of a larger research plan to develop a comprehensive framework for design, analysis, and evaluation of interactive tools that mediate and facilitate the performance of complex cognitive activities. This large framework is called EDIFICE (Epistemology and Design of human InFormation Interaction in complex Cognitive activitiEs). This chapter characterizes some aspects of interactivity in visualization tools, and is therefore referred to as EDIFICE–IVT—where IVT stands for interactivity in visualization tools. Interactivity is not exhaustively characterized here, as such an endeavor is beyond the scope of a single chapter. However, this chapter does approach interactivity in a methodical manner and can therefore provide some systematicity to interactivity research and design. Section 2 provides some necessary background information regarding interaction, interactivity, and some cognitive considerations. Section 3 examines some of the challenges encountered by researchers when discussing interaction and interactivity, and proposes a categorization of interaction and interactivity into multiple levels to deal with some of these challenges. Section 4 identifies and characterizes elements and factors of interactivity at a micro and at a macro level, and provides a design scenario. Finally, Sect. 5 provides a summary of the chapter.

2 Background

Modern visualization tools are used to support the performance of activities such as analyzing terrorist threats [68], making sense of climate change patterns [29], and learning about complex mathematical concepts and structures [39, 40]. Such activities involve mental processes that derive new information from given information in order to reason, solve problems, make decisions, and plan actions [36]. As such activities emerge from the combination and interaction of elementary processes (e.g., perception, memory encoding and retrieval), and take place under complex conditions, they are referred to in the cognitive science literature as complex [18]. In this chapter, we are concerned with how VTs best support complex cognitive activities rather than simpler and lower-level cognitive and perceptual processes. Of particular concern is the manner in which such activities emerge from interactions with VTs. While using VTs, users interact with representations of information displayed at the visually perceptible interface of the tool. Henceforth these are referred to as visual representations (VRs). Examples of VRs include radial diagrams, network graphs, tables, scatterplots, parallel coordinates, maps, and any other visual form that encodes and organizes information. What constitutes a VR within an interface can vary depending on the level of granularity at which the interface is viewed. For instance, the totality of an interface can be considered a VR. However, the interface may also be said to contain a number of distinct VRs (e.g., a map, a table, a scatterplot, and so on). Furthermore, each of these could be considered to be made up of different VRs (e.g., the map may contain any number of glyphs). In this chapter we are concerned specifically with interactive VRs and not with static representations. Henceforth, the term 'VR' implies 'interactive VR'.

2.1 Interaction and Interactivity

Broadly speaking, interaction refers to a reciprocal active relationship—that is, action and reaction. The suffix 'ity' is used to form nouns that denote a quality or condition. In this chapter, interactivity refers to the quality of interaction between a user and a VT. By defining interaction and interactivity in this manner, a clear distinction is made between them and each can be analyzed and developed in relative independence. The distinction is important since a VT may be highly interactive, but if the quality of the interaction is not good, the system will not support the cognitive activities of its users effectively.

One way to conceptualize this difference is in the context of a user performing an individual interaction. An interaction may be thought of as having both an ontological and an operational aspect. The ontological aspect is concerned with *what* the interaction is and what its goal is. For instance, filtering refers to a user acting upon a VR to have only a subset of it displayed according to some criteria. The operational aspect is concerned with *how* an action is performed. For instance, a user may issue a textual command through a keyboard to operationalize the filtering interaction. On the other hand, the user may click and drag on a slider to achieve the same result. The manner in which an interaction is operationalized has been shown to have a significant effect on the quality of a user's interaction with a VT (see [38]). The ontological aspect—what an interaction is and what its characteristics are—is concerned with the interaction itself, whereas the operational aspect—how the interaction is put into use—is the concern of interactivity.

The concept of interactivity has been discussed previously in the literature of various domains; its use and characterization, however, has often been vague and haphazard. Within the past decade researchers have referred to the characterizations of interactivity in the literature as "exceedingly scattered and incoherent" [31], "vague and all-encompassing" [21], "blurry" [1], "lacking in an underlying model" [44], "lack[ing] a common language" [60], and "undertheorized" [8]. Although some researchers have attempted to characterize interactivity, much of the research has been done in the context of media and communication studies (e.g., [8,15,26,31,37]) and advertising and marketing (e.g., [20, 41, 72]). The focus of such research is often on human-human communication, brand perception, communication medium, and social information exchange. As a result, the research in these areas does not necessarily transfer well to the domain of interactive visualizations.

Although visualization researchers have been focusing on different elements of *interaction* in recent years (e.g., [5, 19, 43, 52, 66, 71]), very little attention has been paid to *interactivity*. Some effort has been made to characterize interactivity in the context of educational technologies (e.g., [60]). However, as the function of educational technologies is often very specific (e.g., engaging users in deep and effortful processing of information), such research is not necessarily generalizable to all VTs. In addition, these previous characterizations have not been exhaustive, and the research community would likely benefit from a more systematic and thorough characterization of interactivity that is applicable to all VTs.

As research from a human-centered perspective is fundamentally concerned with how VTs best support human cognition, it is helpful to briefly examine developments within cognitive science research and their implications for the design, use, and evaluation of VTs.

2.2 Cognitive Considerations

Research in various branches of cognitive science over the past few decades has demonstrated that human cognition is fundamentally influenced by the environment in which one is situated [7, 11, 12, 24, 35, 55]. Recent characterizations of human cognition as a phenomenon that emerges from interactions among the brain, body, and external environment have supplanted older models depicting human cognition as an internal phenomenon consisting of symbolic computation—a type of ‘software’ running on neural ‘hardware’. Indeed, research that has been conducted on the use of external resources for cognitive purposes has demonstrated that human cognition is deeply intertwined with phenomena that are external to the brain and body (e.g., see [35]).

Although a deep understanding of human cognition is necessary for research in human-centered visualization, the development of VTs is often uninformed by research in cognitive science [22]. This condition is being noticed by researchers in the visualization community. For instance, recently Arias-Hernandez et al. [6] have stated that “these understandings [in visualization research] still rely on traditional cognitive models that focus on universalisms and assumptions of humans as passive cognitive agents while downplaying recent models that emphasize the situatedness and active role of humans in tight couplings with external representations-processes.” A more systematic incorporation of cognitive science research would certainly benefit visualization researchers and practitioners.

One recent development in the study of human cognition that is particularly relevant for VTs is the theory of distributed cognition. This theory posits that the unit of analysis for cognition should include elements external to one’s brain and body that contribute to cognitive processes. Cognition may be socially distributed, temporally distributed, and/or distributed across internal and external structures and processes [23]. Consequently, the unit of analysis of cognition is not restricted to the brain or even the body alone—it includes socio-technical systems such as the bridge of a ship [24] or an airline cockpit [25], and human–artifact systems such as a person using a pencil and paper [9]. The theory of distributed cognition is being used more and more in recent years in the visualization community to conceptualize various aspects of design and evaluation of VTs (e.g., see [29, 42, 52, 53, 59, 60, 62, 69]). In this chapter we are concerned with the distribution of cognitive processes across an individual and a VT. As a result, the unit of analysis is the human–VT system, and of particular concern is the strength of the coupling among these two components. The quality of interaction—the interactivity—of a VT is a direct result of the strength of the coupling of this human–VT system. In another chapter of this book, the distribution of information processing that occurs within the human–VT system during the performance of complex cognitive activities is analyzed in detail (see [50]).

When users interact with VTs, cognitive processes emerge from a coupling that is formed between the internal representations and processes of the user and external representations and processes at the interface [11, 34, 55]. Although research has determined that the quality of this coupling is vital to the performance of complex cognitive activities, visualization researchers have tended to overemphasize the importance of external representations (i.e., VRs) and underplay the importance of internal representations and how they are coupled through interaction [6]. This is not to say that proper design and analysis of VRs is trivial; rather, the point is that the user and the VT must be considered as a dynamic system, and the effects of each on the other must be given appropriate consideration (see [49] for a discussion of the cognitive utilities of different VRs).

Although working with a static representation to support cognitive activities engages external cognition and creates a coupling, the coupling is not very strong. During the performance of complex cognitive activities, users are forced to adapt to the characteristics of static representations and to make extrapolations regarding information that is not encoded. When representations are made interactive, however, there is potential for strong coupling, and users can adjust VRs to meet their contextual and cognitive needs. In addition, as cognitive processes are intrinsically temporal and dynamic, interactive VRs potentially create a harmony and a tight temporal coupling with cognitive processes [32, 33]. As part of this dynamically coupled cognitive system, the user and the VT each have a causal influence—in other words, the user and the VT are continuously affecting and simultaneously being affected by each another (see Clark's discussion of continuous reciprocal causation in [10]).

The ultimate implication here is that complex cognitive activities are circumscribed by the features of the environment and, in particular, by the strength of the coupling between internal mental processes and external representations of information. As interaction with VTs forms a coupled system in which there is reciprocal causal influence, we cannot understand or discuss complex cognitive

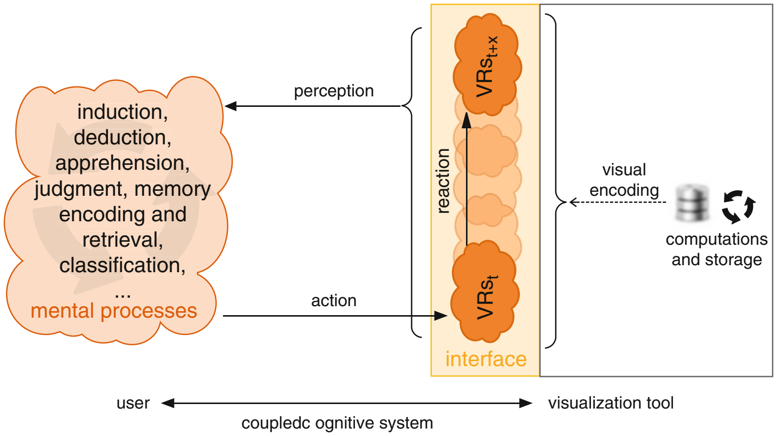

Fig. 1 The coupling that is formed between a user and a visualization tool

activities without examining the ways in which such activities are constrained, canalized, or enhanced by the tools that are supporting the activities. It is important to realize that the process of performing activities is as much driven by the characteristics of tools as it is by the characteristics of users [33]. It is necessary, therefore, to examine the elements and factors that affect the quality of interaction with a VT. Some elements and factors will be identified and developed in Sect. 4 (see Fig. 1).

3 Levels of Interaction

The interaction that takes place between a user and a VT can be characterized at multiple levels of granularity. Here we propose that interaction be categorized into four main levels: activities, tasks, actions, and events. Activities occur at a high level and are often complex and open-ended (e.g., problem solving, decision making, and forecasting); tasks are goal-oriented behaviors that occur at a lower level during the performance of activities (e.g., categorizing, identifying, and ranking); interactions occur at an even lower level and involve actions that are performed upon an interface (e.g., annotating, drilling, and filtering) and their consequent reactions; events occur at the lowest-level of physical interaction with a VT and are the building blocks of interactions (e.g., mouse clicks, keyboard presses, and finger swipes). There are also minor levels among these major ones. Activities often involve sub-activities; tasks often involve sub-tasks and visual tasks; and interactions involve lower-level conceptual steps and implementation techniques.

One of the main challenges of characterizing interaction and interactivity is that there are many levels at which they may be viewed. This presents an especial challenge for using language that accurately conveys the level of granularity that is being discussed. For instance, consider comparing as an interaction. A user can compare at the level of an individual interaction, by acting upon a VR and receiving a reaction that communicates its degree of similarity to another VR. The user can also compare at the higher level of performing a task, by combining and linking multiple interactions together to determine the degree of similarity of a number of VRs. Additionally, although not an interaction, the user can compare at the level of perceptual tasks that involve pre-attentive visual comparisons. It is often the case in the visualization literature that no distinction is made among these levels. This simple example highlights the necessity of having an accurate language for discussing interaction. Conceptualizing interaction as having multiple levels can mitigate this issue and facilitate more consistent discourse using a common vocabulary. In this chapter, we have attempted to discuss these levels in a consistent manner. The catalog discussed below, for instance, attempts to give some structure to interaction at a particular level—at a level that is higher than physical events, low-level conceptual steps, and interaction techniques, but is lower than tasks and complex activities. This type of consistency can help to clarify and give structure to the landscape of interaction and interactivity design.

In previous years, researchers were concerned with designing and evaluating interactive technologies to effectively support relatively simple and highly structured tasks, such as entering data into spreadsheets, composing letters and other documents, sending emails, locating particular files on a hard drive, and organizing files and folders. Numerous models were constructed and/or used to characterize user activity. Hierarchical task analysis, GOMS, and cognitive task analysis are examples of models that were used in the HCI community to characterize user interaction with technology. The utility of such models is their rigorous and highly structured characterizations of user activity. Their descriptive and prescriptive abilities, however, seem to fall short in the context of open-ended, unstructured, and complex activities. Visualization researchers have also devised descriptive models of user activity. Examples include the Information Seeking Mantra [67]: *overview, zoom, filter, and details on demand* and the Visual Analytics Mantra [30]: *analyze first, show the important, zoom, filter and analyze further, details on demand*. In a similar manner, these models are not sufficient for capturing the richness of deep and complex activities.

Characterizing interaction at multiple levels in order to discuss interactivity can help deal with some of the challenges mentioned above. For example, the dynamics of complex cognitive activities in a user-VT system can be conceptualized in terms of both embeddedness and emergence. That is, lower levels are embedded within one another. A ranking task, for instance, may involve the actions of filtering, selecting, and arranging. Each action may involve any number of low-level conceptual steps and physical events. Conceptualizing interactivity in terms of embeddedness allows for clear decomposition of phenomena into constituent component parts at lower levels. This analytical approach is typical of much of the early research in interaction as mentioned in the previous paragraph. Such an approach is highly useful for analysis, and allows for precise characterizations of interaction, especially at lower levels of granularity. Unlike simple tasks, however, complex cognitive activities are nonlinear and emergent phenomena [46].

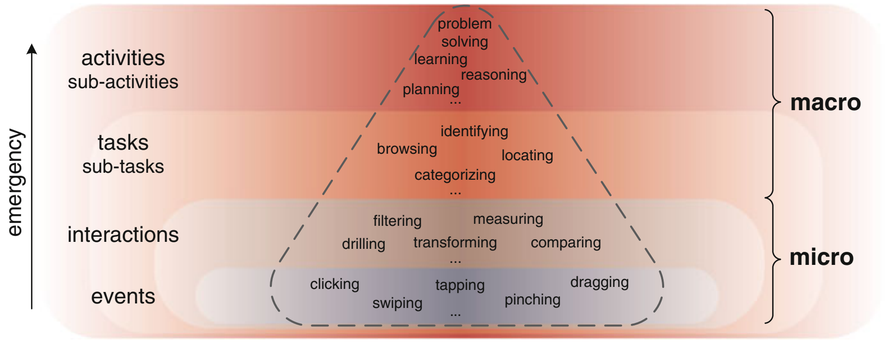

Fig. 2 Interaction categorized into four main levels

Accordingly, the manner in which users perform interactions with a VT to engage in complex activities are often nonlinear and do not follow a pre-determined path [32, 63, 68]. During the course of such activities, although user goals typically have some stability over time, they often undergo changes—in other words, the constituents of an activity are not fixed but can dynamically change as conditions of the activity change [48]. If interaction with tools is treated as a rigid and formulaic process, then we risk missing the dynamics that emerge from sustained interaction with a tool [32]. Therefore, at higher levels, emergent properties occur as a result of the combination of phenomena at lower levels. As complex cognitive activities often do not follow a pre-determined plan, precisely describing the path of an activity is not possible. What can be done, however, is to understand the elements and factors that contribute to the interactivity of a VT and create an environment that best supports the emergence of complex cognitive activities. Such an approach combines the strength of an analytic strategy of decomposing lower levels of activity into component states and processes as well as a synthetic strategy that supports emergence at higher levels (Fig. 2).

In this chapter, interactions are viewed at the level of general patterns of action and reaction that have an epistemic benefit, rather than as more concrete techniques or instantiations of patterns. Sedig and Parsons [63] have recently devised a framework that contains a catalog of over 30 epistemic action patterns, and have discussed the utility of each for performing complex cognitive activities. Table 1 provides a list of some of these patterns. In this catalog, each action is characterized in a conceptual, pattern-based fashion in terms of its epistemic benefit. As a result, there can be many variations of a pattern and many techniques for implementing an instance of an action pattern in a VT. For example, consider the action pattern of *arranging* that is identified and characterized in the catalog. This action pattern refers to a user acting upon VRs to change their ordering and spatial organization within the interface. Variations of this pattern include moving, ranking, ordering, and sorting. In other words, each of these variations consists of a user acting upon VRs to change their ordering and spatial organization within the interface. In addition, each of these may consist of any number of conceptual steps and/or events at the physical level of interaction with the VT.

Table 1 Some action patterns from the catalog of Sedig and Parsons [63]

Action	Description
Animating	Generating movement within VRs
Annotating	Augmenting VRs with additional visual marks and coding schemes, as personal meta-information
Arranging	Changing the ordering and organization of VRs, either spatially or temporally
Blending	Fusing VRs together such that they become one indivisible, single, new VR
Cloning	Creating one or more copies of VRs
Drilling	Bringing latent, interior information to the surface of VRs
Filtering	Displaying only a subset of information in VRs
Measuring	Quantifying VRs in some way (e.g., by area, length, mass, temperature, or speed)
Searching	Seeking out the existence of or locating information in VRs
Scoping	Dynamically working forwards and backwards to view the compositional development and growth of VRs
Transforming	Changing the geometric form of VRs
Translating	Converting VRs into alternative informationally- or conceptually-equivalent forms

4 Characterizing Interactivity

Just as interaction can be conceptualized as having multiple levels, so can interactivity be conceptualized in this manner. In this chapter we categorize interactivity into two main levels: a micro level and a macro level. Interactivity at the micro level emerges from the structural elements of individual interactions. Interactivity at the macro level emerges from the combination of individual interactions to perform tasks and activities. Sections 4.1 and 4.3 will characterize and discuss some considerations of interactivity at the micro level and at the macro level respectively.

4.1 Micro-level Interactivity

As we are concerned with individual interactions at a general, pattern-based level (see Sect. 3), any interaction has a number of elements that collectively give it structure. Interactivity at the micro-level emerges from these elements. As discussed earlier, each individual interaction has two components: action and reaction. The manner in which the action and reaction components of an interaction are operationalized affects the strength of the coupling between a user and a VT. Each element has different operational forms, and varying the operationalization of these structural elements determines the quality of the interaction. Currently, we have identified 12 elements—6 for action and 6 for reaction. The elements of action are: presence, agency, granularity, focus, flow, and timing. The elements of reaction are: activation, flow, transition, spread, state, and context. In what follows, we will characterize each element and discuss some possible ways in which each can be operationalized (Fig. 3).

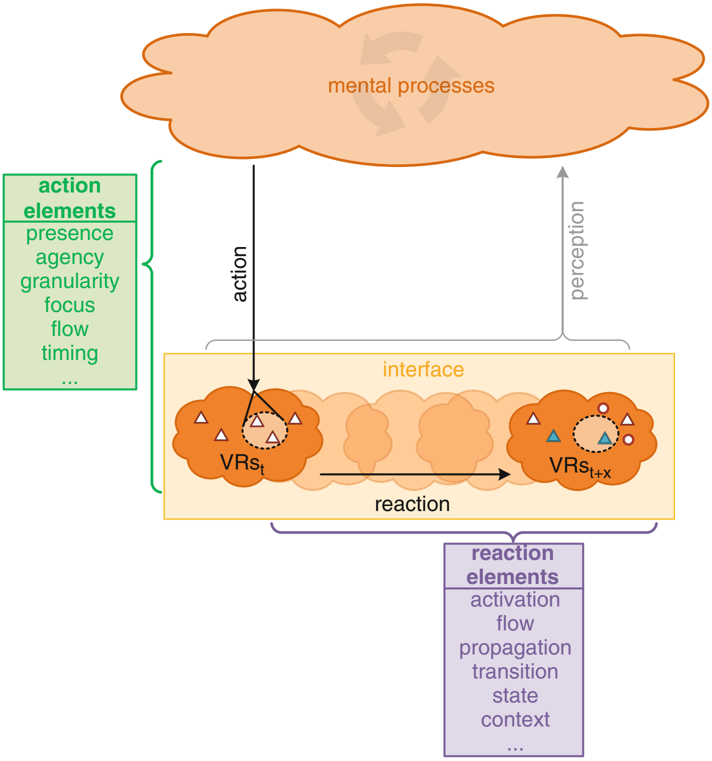

Fig. 3 Some structural elements of an individual interaction

4.1.1 Action Component

There are at least six elements that make up the action component of an interaction. These are discussed next.

Presence. This element is concerned with the existence and advertisement of an action. In other words, this element is about the cue or signal from the visualization used to prompt the user or advertise the existence of the interaction. Two of the main forms of this element are: explicit and implicit. If presence of an action is explicit, the availability, existence, or provision of the interaction is explicitly advertised by the tool, such as when a label or tool tip is used to let the user know that the interaction exists. When presence is implicit, the interaction exists, but its availability is either not easily perceptible by the user, or it is not visible at the interface level. In this case, the user must know of the existence of the interaction, or it would seem to the user that the interaction were non-existent.

Agency. This element is concerned with the metaphoric agency through which an action is expressed. Once the user knows of the existence of an action, the action must be articulated in some manner. Some of the main forms that this element can assume include: verbal, manual, pedal, and aerial. Through verbal agency, actions are expressed through the user's 'mouth' (e.g., text menus, commands, or natural-language speech); that is, it is as if the user speaks to the VRs. Using this form, the VRs are viewed as entities that understand linguistic commands and react to them. Through manual agency, actions are expressed through the user's 'hands' (e.g., a pointing cursor); that is, it is as if the user's hand reaches into the VRs and touches and grasps their visual components. Using this form, the VRs are thought of as objects that can be handled and manipulated. Through pedal agency, actions are expressed through the user's 'feet' (e.g., an avatar that walks); that is, it is as if the user walks on a terrain. Using this form, the VRs can be regarded as maps on which the user moves. Finally, through aerial agency, actions are expressed through the user's 'wings'; that is, it is as if the user flies over or through the VRs. Using this form, the VRs are thought of as space through which the user can navigate. It is important to note that the last two forms are very similar as they both express an interaction through navigation. An example of aerial means of an interaction is when the user can fly in a 3D VR and gets near a visual element. Upon reaching a certain distance, the visual element can be drilled to provide extra information to the user. As the user flies away, the extra information can disappear.

Granularity. This element is concerned with the constituent steps of an action. There are two main forms of granularity: atomic and composite. If the granularity of an action is atomic, the action cannot be decomposed into further steps—i.e., there is only one step. If the granularity of an action is composite, the action requires more than one step. As the interaction construct is at a higher level than low-level physical events, an action may be operationalized in different ways such that there are different granularities in different contexts. In other words, since interactions are not characterized at the lowest possible level, the constituent parts of an action pattern are variable. To clarify and illustrate this element, let us examine a VT, Super Tangrams (see [58]). This is an interactive game in which children use transformation geometry operations to rearrange visual shapes and fit them into an outline without the shapes overlapping. Solving each puzzle requires a set of interactions. Consider the user moving a shape—a variation of the *arranging* interaction pattern discussed above. In order to move the shape (i.e., perform one interaction), the user must go through the following steps: choose the shape, choose an operation (e.g., rotation), adjust the parameters of the operation (e.g., angle of rotation and center of rotation), and finally press a 'Go' button. In this case, the action has composite granularity. This same interaction can be designed to have atomic granularity. For instance, the user can choose a shape that has pre-determined parameters simply by clicking on the shape, and then the reaction ensues automatically without the need to press a 'Go' button. In other words, the action in this case cannot be decomposed into multiple steps.

Focus. This element is concerned with the focal point of an action. Two of the main forms of focus are: direct and indirect. If focus of an action is direct, the action is expressed by the user directly acting upon the VR. If the focus of action is indirect, the action is expressed by the user operating on other intermediary interface representations in order to communicate with and cause a change in the VR of interest. As an example, consider a VR of a human heart that a user wishes to slice open to make sense of its internal components. If the focus of action is direct, the user could click on the VR to open the heart. If the focus of action is indirect, the user may select an anatomical feature from a list to have the VR of the heart open to expose that feature.

Flow. This element is concerned with how an action is parsed in time. Two main forms of flow are: discrete and continuous. If the flow of an action is discrete, the action occurs instantaneously and/or is punctuated. If flow of an action is continuous, the action occurs over a span of time in a fluid manner. For example, a user may be viewing a VR of a scientific co-citation network for the year 2005 and want the VR to display the network for 2010. The user may click on a button that says '2010'—that is, the action flow is discrete. The user may also click on a slider at its current position and drag it until it is at 2010—an example of continuous action flow. One study found that the manner in which action flow is operationalized has a significant impact on the cognitive processes of the user (see [38]).

Timing. This element is concerned with the amount of time the user is given to compose and/or commit an action. There are two main forms of action timing: user-paced and system-paced. User-paced timing allows the user to compose and commit an action at his or her own pace. Using this form of timing, the user has as much time as needed to think about and examine a situation before committing an action. Even when the flow of action is discrete, the user may choose to take any amount of time before the discrete submission of the action. If action timing is system-paced, however, the user has a limited time to compose and perform an action.

4.1.2 Reaction Component

There are at least six elements that make up the reaction component of an interaction. Collectively these six elements can also be referred to as feedback. Even though feedback is discussed by many researchers, it is often presented as an all-encompassing construct that does not distinguish between different levels of interaction and interactivity. Visualization researchers and practitioners would benefit from having a clearer characterization of the elements that make up the structure of feedback at the level of each interaction. As this chapter is concerned with human-centered interactivity, reaction refers to the effects of an action that are visually perceptible at the interface, and not those that may take place internally in the VT and are hidden from view of the user. In addition, as users and VTs are coupled into one cognitive system, using language from systems theory can facilitate conceptualization of the reaction component and its elements. Interfaces are subsystems of a broader user-VT system. Interfaces are also open systems—they receive some input from the user (i.e., an action) and provides some output to the user (i.e., a reaction). During the reaction process, the interface goes through fluctuations before reaching equilibrium. As a result, some of the reaction elements deal with the reaction during fluctuation while others deal with the reaction as the interface reaches equilibrium.

Activation. This element is concerned with the point at which the reaction begins. There are at least three main forms of activation: immediate, delayed, and on-demand. If activation is immediate, the interface reacts to the user's action instantaneously. If activation is delayed, there is a temporal gap between the user's action and the reaction. Finally, if activation is on-demand, the reaction does not take place until requested by the user. Immediate activation of reaction is often discussed in the literature—and is often referred to as 'immediate feedback'—as the only desirable form of activation. While this may be true for most productivity VTs, there are applications in which delayed and on-demand activation are useful (see [4]).

Flow. This element is concerned with how a reaction is parsed in time. There are two main forms of flow: discrete and continuous. In discrete flow, the reaction occurs instantaneously and/or is punctuated. In continuous flow, the reaction occurs over a span of time in a fluid manner. For example, consider a user making sense of climate change patterns with a 3D VR of the earth. If the user is viewing temperature patterns at a point in time (e.g., 1950), during the activity she can perform an action to request that the VR display the temperature at a different point in time (e.g., 2010). The flow of the reaction may be discrete—that is, the temperature patterns for 2010 appear instantaneously or the change is punctuated and has discrete intervals. On the other hand, the flow of the reaction may be continuous—that is, the change from 1950 to 2010 takes place over a span of time in a fluid manner. One study found that the manner in which reaction flow is operationalized has a significant impact on the cognitive processes of the user (see [38]).

Transition. This element is concerned with how change is presented. As an interactive VR is a spatio-temporal entity, its changes can be presented either by distorting its temporal dimension or its spatial dimension. Hence, there are two general types of transition: stacked and distributed. With stacked transition, changes are sequentially stacked on top of one another so that only the current frame of the changing VR is visible. In distributed transition, a number of visualizations capture and preserve instances of the changing VR and present them spatially—in other words, the temporal dimension of the changing VR is distorted and is presented as parallel visualizations distributed in space. To examine the difference between the two forms, consider an educational VT that supports learning about molecular biology. Such a VT may display a VR of a cell with which the user can learn about mitosis. A user can act upon the VR so that there is a transition from the current state of the cell to the end of a mitosis process. If the transition of the reaction is stacked, the subsequent states of the mitosis process will be displayed on top of one another. If the transition is distributed, subsequent phases of the transition will be displayed spatially in different locations. One study found that the different forms of transition had significantly different effects on cognitive processes of the user (see [64]).

Spread. This element is concerned with the spread of effect that an action causes. When an action is performed, it can cause change not only in the VR of interest, but also in other VRs. There are two main forms of spread: self-contained and propagated. In the self-contained form, the VR of interest is the only VR that is affected by the action. In the propagated form, the effect of the action propagates to other VRs in the interface. Consider a VT that supports forecasting of financial outcomes for a company. The interface may contain five separate VRs—one for each of accounting records, projected revenue, sales data, market indicators, and the period of time that is being considered. If an action is performed, the spread may affect only the VR of interest (e.g., acting upon the VR of market indicators to show or hide a subset of the possible indicators). The effect may also be propagated to other VRs (e.g., acting upon the VR of accounting records and having the change spread to the VR of projected revenue so that it is updated).

State. This element is concerned with the conditions of the interface (i.e., the interface's VRs) once the reaction process is complete and the interface reaches equilibrium. There are three main states that VRs affected by an action can take: created, deleted, and altered. VRs that have been affected by an action may be in a created state—that is, they did not exist before the activation of the reaction, but were created during the reaction process and are now visually perceptible at the interface. VRs that have been affected by an action may also be in a deleted state—that is, they did exist before the activation of reaction, but were deleted during the reaction process and are no longer visible. Finally, VRs that have been affected by an action may be in an altered state—that is, they did exist before the activation of reaction, and still exist as the interface reaches equilibrium, but some of their properties have been altered.

Context. This element is concerned with the general context in which VRs exist as the interface reaches equilibrium. Before the activation of a reaction, there is some context in which a VR exists. A reaction either maintains this general context or effects a change in context. Hence, there are two main forms of this element: changed and unchanged. There is an important difference between context and state. A VR may be created or deleted, for instance, but the general context in which the VR exists can remain unchanged. As an example, consider a VT for public health informatics. A user can perform an annotating action on a VR by highlighting or attaching a note to it. As the interface reaches equilibrium (i.e., the reaction has occurred and the annotation is displayed), the context in which the VR exists is unchanged and is the same as it was prior to the reaction. The user may perform a drilling action on the same VR that results in new information about a particular disease appearing and temporarily replacing the previous information, thus changing the context.

As was mentioned above, these 12 elements collectively contribute to the structure of any individual interaction. In addition, as discussed in Sect. 2, the interface of a VT can contain any number of individual VRs. Consequently, the different forms of these structural elements are not necessarily mutually exclusive. For instance, in the study conducted by Sedig et al. [64], in one of the test versions of the VT, an action resulted in both forms of transition in two different VRs.

Table 2 Micro-level interactivity considerations

Component	Element	Concern	Forms
Action	Presence	Existence and advertisement of action	Explicit, implicit
	Agency	Metaphoric agency through which action is expression	Verbal, manual, pedal, aerial
	Granularity	Constituent steps of action	Atomic, composite
	Focus	Focal point of action	Direct, indirect
	Flow	Parsing of action in time	Discrete, continuous
	Timing	Time available for user to compose and/or commit action	User-paced, system-paced
Reaction	Activation	Point at which reaction begins	Immediate, delayed, on-demand
	Flow	Parsing of reaction in time	Discrete, continuous
	Transition	Presentation of change	Stacked, distributed
	Spread	Spread of effect that action causes	Self-contained, propagated
	State	Condition of VRs as interface reaches equilibrium	Created, altered, deleted
	Context	Context in which VRs exist as interface reaches equilibrium	Changed, unchanged

The study showed that operationalizing these different forms simultaneously in different VRs had a significant effect on the cognitive processes of the users. Moreover, different operational forms can be combined in a single interaction. In another tool, Super Tangrams [58], an action that has composite granularity can exhibit both continuous and discrete flow as the steps are put together to perform the action. These combinations and their effects on the strength of coupling between users and VTs requires further explication in future research. When these elements and their forms are brought together and used in the design and evaluation of VTs that support cognitive activities many combinations are possible. For instance, an interaction may be operationalized with direct focus of action, discrete flow of action, and continuous flow of reaction. The same interaction may be operationalized with indirect focus of action and the same forms of action and reaction flow. Alternatively, the focus of action may be direct, the flow of action discrete, and the flow of reaction also discrete. Section 4.2 gives a design scenario to facilitate thinking about the combination of different operational forms of the structural elements that are listed in Table 2.

4.2 EDIFICE–IVT: Design Scenario for Micro-level Interactivity

The following scenario illustrates the potential for micro-level interactivity considerations to inform the design of visualization tools. An awareness of the different interaction elements and some of their possible forms enables designers

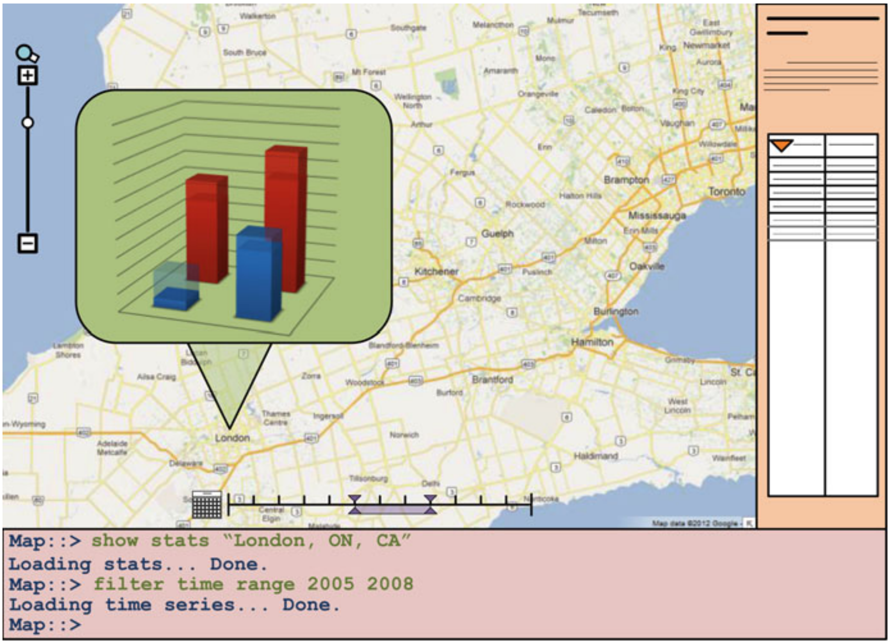

Fig. 4 A user filtering a VR

to operationalize them in a deliberate manner. Consider the design of a map-based visualization tool that supports analysis and sense making of sales data for different cities in a region. At some point the user will need to drill into the map VR to bring to the surface information about sales data for particular cities. Figure 4, for example, depicts an interface after the user has drilled into a city, causing two VRs to appear: a three-dimensional bar graph and a table. The rest of the scenario will describe how further interactions with such a VT may be operationalized using different forms. Figures 4–7 depict different ways of operationalizing the same interaction: filtering out all of the sales data except for a particular time period.

Figure 4 depicts the user filtering the VR to show sales data during the period of 2005–2008 only. The operational forms of the action component are: implicit presence—the user performs an unadvertised action and must know the proper input command; verbal agency—the user types a linguistic command to the VR; composite granularity—there are two constituent steps of the filtering interaction: typing the command and then pressing 'enter'; indirect focus—the VR of interest is the bar graph and the focal point of action is the command line; continuous flow—the action takes place over a period of time while the user is typing; and, user-paced timing—the user has no time limit on committing the action. The operational forms of the reaction component are: immediate activation—once the user commits the action the reaction begins without any delay; continuous flow—the reaction occurs fluidly (shown as transparent sections of the bars); stacked transition—change is

Table 3 Operational forms of action elements in Figs. 4 –7

Figure	Presence	Agency	Granularity	Focus	Flow	Timing
4	Implicit	Verbal	Composite	Indirect	Continuous	User-paced
5	Explicit	Manual	Composite	Indirect	Continuous	User-paced
6	Explicit	Manual	Atomic	Direct	Continuous	User-paced
7	Explicit	Manual	Atomic or composite	Indirect	Continuous	User-paced

Table 4 Operational forms of reaction elements in Figs. 4 –7

Figure	Activation	Flow	Transition	Spread	State	Context
4	Immediate	Continuous	Stacked	Propagated	Altered	Unchanged
5	Immediate	Continuous	Stacked	Propagated	Altered	Unchanged
6	Immediate	Continuous	Stacked	Propagated	Altered	Unchanged
7	Immediate	Discrete	Distributed	Propagated	Altered	Unchanged

presented by stacking frames on top of one another and not by distributing them spatially; spread is propagated—the table is also affected by the action; altered state—no VRs are created or deleted but are only altered as the interface reaches equilibrium; and, unchanged context—the context in which the VRs exist stays the same as the interface reaches equilibrium.

The previous paragraph should give readers an idea of how an individual interaction can be analyzed according to its structural elements. It should also give the reader a sense of how the operationalization of these elements can affect the interactivity of a VT at a micro level. For the sake of brevity, the next few examples will not identify the form of every element, but will discuss only a subset. All of the elements and their operational forms are listed, however, in Tables 3 and 4.

Figure 5 depicts the user performing the same interaction—filtering—but with a different operationalization. In this case, the user chooses the filtering period by dragging a slider from one spot to another (2005–2008) and then presses a 'go' button. Unlike the interaction described above and shown in Fig. 4, the action presence is explicit and the agency is manual; the granularity, focus, flow, and timing, however, are all the same. In this case, the operational forms of reaction elements are exactly the same as in Fig. 4. In the case of Fig. 6, the focus of action is direct—the user acts directly upon the bar graph VR to filter it—and the granularity is atomic. The other elements are operationalized the same as in Fig. 5. The reaction elements are also operationalized in the same manner. In the case of Fig. 7, the action is the same, but the reaction is operationalized differently. In all previous examples the transition of reaction was stacked; in this case, however, the transition is distributed. Multiple visualizations capture and preserve instances of the changing VR and present them spatially—that is, the temporal dimension of the changing VR is distorted and is presented as parallel visualizations distributed in space.

The examples discussed above do not constitute an exhaustive design scenario. This section only briefly explores a small number of design options to demonstrate how EDIFICE–IVT can facilitate analysis and design of micro-level interactivity in visualization tools. Using such a framework, designers can methodically analyze

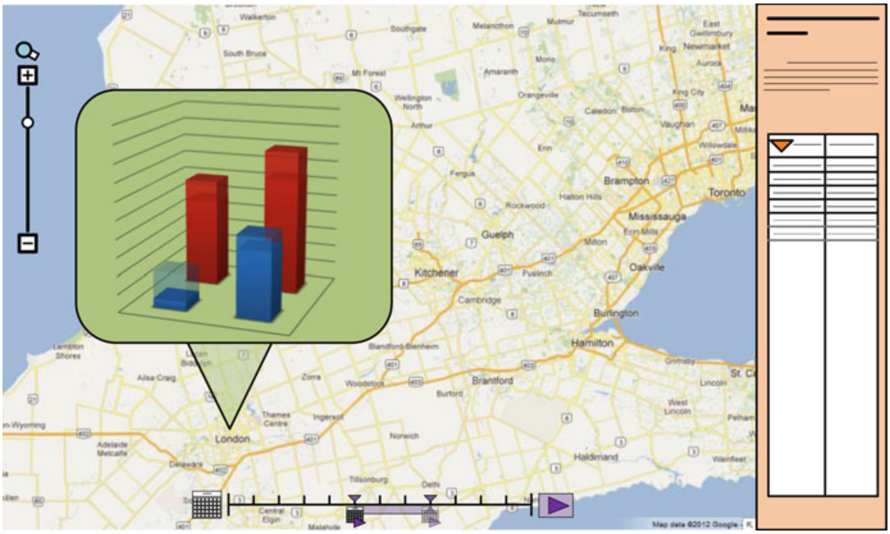

Fig. 5 A different operationalization of the same interaction shown in Fig. 4

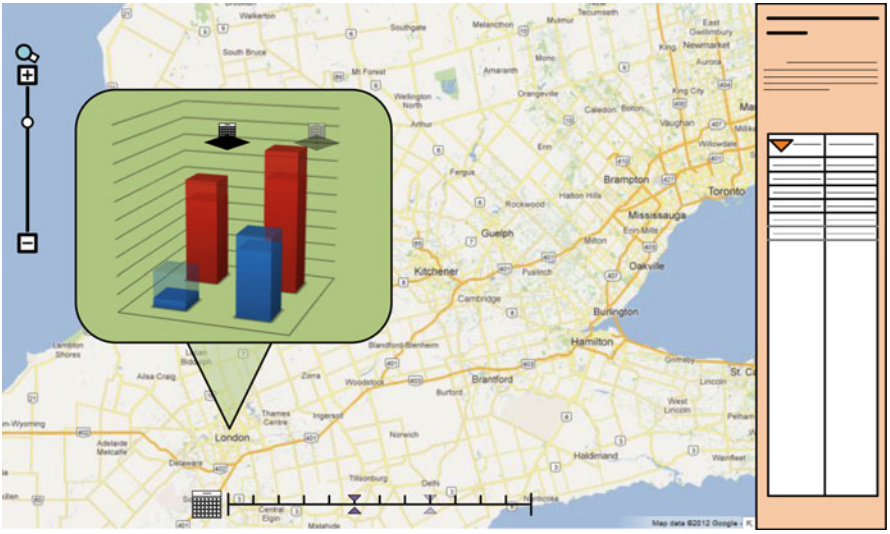

Fig. 6 An example of direct focus of action

the combinatorial possibilities that the operational forms of interaction elements create in terms of design variations for VTs. For example, if each interaction has 12 elements, each of which has at least 2 forms, the number of possible ways to operationalize an interaction is at least 2^{12}, or 4,096. It should be noted that not all elements are applicable or have significant cognitive effects in every VT. However,

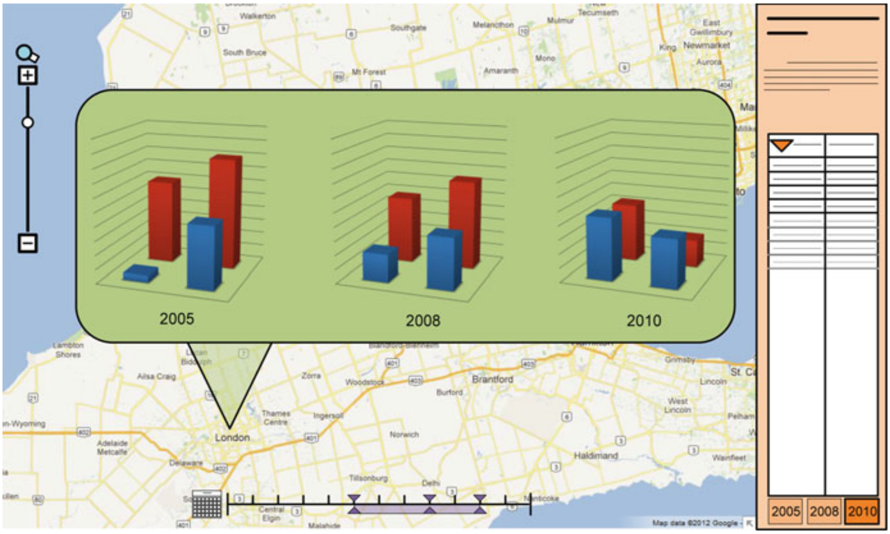

Fig. 7 An example of distributed transition of change

even if only half the elements have a significant influence on cognitive processes in a particular context, the possible combinations are at least 2^6, or 64. Without a descriptive, analytical framework, such as the one presented here, it would be very difficult to consider the many possibilities for design in a systematic manner.

4.3 Macro-level Interactivity

In this section, we analyze macro-level interactivity—interactivity at the level of multiple interactions being combined and put together to perform tasks and activities. This analysis deals with the factors that affect the overall quality of interaction, as well as the properties and relationships of its aggregated interactions and how interactivity emerges from these. As discussed in Sect. 3, activities can be viewed at multiple levels of granularity, with phenomena at lower levels being embedded within those at higher levels. For instance, the activity of making sense of a complex 3D geometric structure may include a task, such as identifying different objects and sub-structures. This task may in turn have several interactions embedded in it, such as filtering, scoping, and annotating [63]. Therefore, macro-level interactivity emerges from the whole interface of a VT—that is, the properties of all its interactions and the relationships of these interactions with each other. In what follows, we will characterize and discuss five of the factors that we believe affect the quality of interaction at a macro level. These five factors are: diversity, complementarity, fitness, flexibility, and genre.

Diversity. This factor is concerned with the number and diversity of interactions that are available to the user. A multiplicity of interactions allows the user to perform different types of cognitive tasks. Some studies show that providing a diverse set of interactions in a VT can have a positive effect on reasoning and other cognitive activities [40, 65]. Such diversity can encourage more autonomous and self-regulated cognitive processes. However, van Wijk [70] points out that although interaction is generally good it should be used carefully, as there are costs associated with the number of interactions. Both too few as well as too many interactions can be costly. In an empirical study involving mathematical visualizations, Liang and Sedig [40] demonstrate that lack of interactions can make exploration of the visualizations ineffective and inefficient. The same study also shows that having many interactions may result in some costs due to high time consumption and cognitive demand. When there are too many interactions, the user may need to spend time trying out all available interactions, figuring out their functions and benefits, and remembering how and when to use them. As such, even though some degree of diversity can generally result in positive benefits, it should be balanced.

Complementarity. This factor is concerned with harmonious and reciprocal relationships among interactions, and how well they work with and supplement each other. This factor affects the quality of interaction of a tool by allowing the user to conduct more coordinated and integrated cognitive activities. That is, although each individual interaction independently supports one particular action, collectively the interactions can work together and assist the user to perform more complicated tasks and activities. For instance, in a study [40] of an interactive VT for exploring and reasoning about 3D lattices, it was observed that two interactions, filtering and annotating, were used to complement each other in performing certain tasks. Annotating was used to reason about paths by providing mechanisms for labeling and tracing nodes and edges of lattices, while filtering was used to isolate and focus on certain node types and patterns within 3D lattices.

Fitness. This factor is concerned with the appropriateness of interactions for the given VRs, the tasks and the activity, and the user's needs and characteristics. This is a complex and multi-faceted factor, each of its facets may need analysis. Some of these facets include: semantic-fitness, task-fitness, user-fitness, and context-fitness [61]. The first facet, semantic-fitness, deals with whether an interaction can enhance the communicative and semantic utility of a VR. For instance, a VR may be designed to display a 3D geometric shape to communicate its structure—that is, its constituent polygonal faces and their relationships. In such a case, providing rotation as an interaction may not be good for better communicating the semantic features of the 3D shape. This is because the 3D shape is symmetric; rotation may only allow the user to observe partial structures of the VR, while some parts may remain occluded from view. This can make it difficult for the user to fully perceive the structural semantics of the 3D shape. Providing decomposing as an interaction, however, can be more semantically appropriate for communicating the structural semantics of this 3D shape, as it allows the user to break the shape apart and display it as a flat 2D representation, thereby allowing the user to observe and examine its structural semantics with more ease—e.g., observing that the shape has 20 faces, and these are all triangles. In a similar manner, the other facets allow an analysis of the fitness of interactions: task-fitness deals with the suitability of interactions to support a task that involves given VRs; user-fitness deals with whether interactions match the cognitive needs and characteristics of the user (e.g., a child versus an adult); and context-fitness is about whether interactions support the psychological, cognitive, and structural requirements of an environment (e.g., a visual game versus a visual analytics tool). These facets provide a more organized way of thinking about the relevance, conceptual correspondence, cognitive cost, and appropriateness of interactions—and hence the quality and utility of interactions.

Flexibility. This factor is concerned with the range and availability of adjustability options. A highly flexible tool provides options for the user to be able to adjust the properties of the interface to suit his/her needs, characteristics, and goals. For instance, a tool that allows the user to adjust the dimensions of VRs, such as their appearance or density (see [51]), is more flexible than one that does not. Another facet of flexibility is with regard to the order of interactions when performing a task or activity. Some tools can have a very rigid sequencing and path of interactions. However, the final goal of many complex activities can be reached via different trajectories through the representation space of a tool. This is called the principle of equifinality. The interactive features of a flexible tool support this principle. Yet another facet of flexibility is the degree of control that the user has over the micro-level forms of some of the elements of interaction, such as agency, flow, activation, and transition. The flexibility factor can play an important role in the overall quality of interaction.

Genre. This factor is concerned with the types of transactions that are available to the user—that is, interactions through which the user makes exchanges with the VRs. The types of interactions that are provided can be placed on a continuum: allowing the user to only access VRs to allowing the user to only create VRs. As such, a VT's interactions can be classified into different genres: access-based, annotation-based, modification-based, construction-based, and combination-based. Using access-based interactions, the user accesses the stored, available, existent VRs already contained in the tool. Using annotation-based interactions, the user adds further notations or codes to the existing VRs. Using modification-based interactions, the user alters the properties of existing VRs such as by adding to or removing from them. Using construction-based interactions, the user constructs new VRs—VRs that are not necessarily provided in the tool, but rather created, synthesized, and composed from scratch. Finally, using combination-based interactions, the user operates upon VRs with two or more of the previous types of transactions. Consider the interactions listed in Table 1. Arranging, drilling, and filtering are all examples of access-based interactions. With these interactions a user typically does not create, destroy, add to, or modify VRs in any way. Annotating is an example of an annotation-based interaction. The user is not inserting new information in the tools,

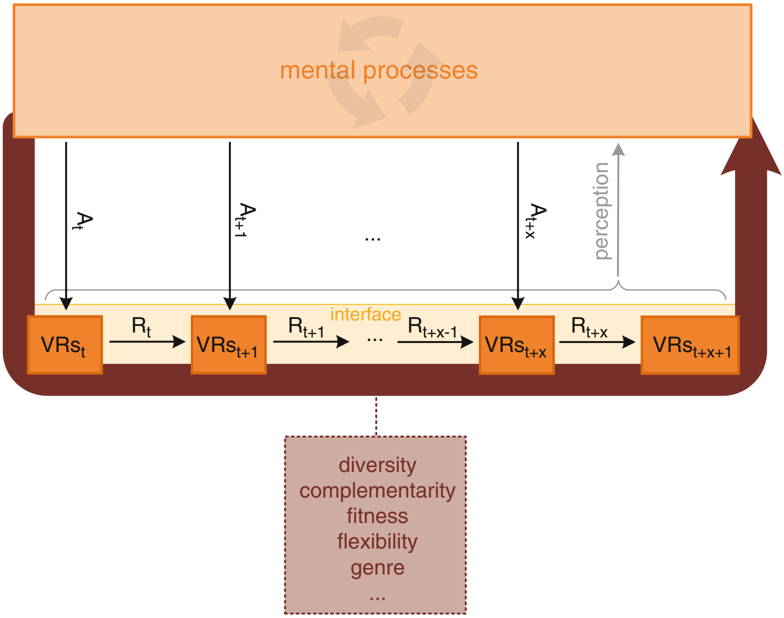

Fig. 8 Some macro-level interactivity factors

but rather is adding meta-information—i.e., a layer of information that highlights and describes—to the existing VRs. Assigning, transforming, and inserting are all examples of modification-based interactions. With these interactions a user adds properties to VRs, removes properties from VRs, adjusts the value of the properties of VRs, and so on. Composing is an example of a construction-based interaction. Once again, as can be seen, the genre of interactions has an overall effect on the macro-level interactivity of a VT (Fig. 8).

5 Summary

For visualization tools to be human-centered, they must be designed with a well-informed understanding of human cognition. However, visualization research is often based on traditional models of cognition that do not emphasize its situated nature and the role that interaction with the external world plays in performing complex cognitive activities. When users interact with visualization tools, cognitive processes emerge from a coupling that is formed between the internal representations and processes of the user and the external representations and processes that exist at the tool's interface. In this chapter, interactivity has been conceptualized as the strength of the coupling—in other words, the quality of the interaction—between a user and a visualization tool.

The framework presented here is a component of a larger framework called EDIFICE (Epistemology and Design of human InFormation Interaction in complex Cognitive activitiEs), and has been referred to as EDIFICE–IVT—where IVT stands for interactivity in visualization tools. EDIFICE–IVT has characterized interactivity at two levels: micro and macro. Twelve structural elements of interaction that affect micro-level interactivity have been identified and characterized. Some of the operational forms that these elements can take have also been identified, and a scenario to demonstrate how these may be considered collectively in the design of VTs has been examined. At the macro level, five factors that affect macro-level interactivity and some possible operational forms of each have been examined. The manner in which these elements and factors are operationalized in a VT affects the quality of interaction and ultimately affects how well cognitive activities are performed. Therefore, having an awareness of the elements and factors that influence interactivity, as well as some of their operational forms, can facilitate systematic thinking about interactivity and deliberate and methodical design practices. In addition, as the discussion of interactivity in the research literature is often vague and inaccurate, EDIFICE–IVT can contribute to a common vocabulary that visualization researchers and practitioners can use to discuss interactivity.

References

1. Aigner, W.: Understanding the role and value of interaction: First steps. In: S. Miksch, G. Santucci (eds.) International Workshop on Visual Analytics (2011)
2. Albers, M.: Design for effective support of user intentions in information-rich interactions. Journal of Technical Writing and Communication **39**(2), 177–194 (2009)
3. Albers, M.: Human-information interactions with complex software. Design, User Experience, and Usability. pp. 245–254 (2011)
4. Alessi, S.M., Trollip, S.R.: Multimedia for Learning: Methods and Development. Allyn and Bacon (2001)
5. Amar, R., Eagan, J., Stasko, J.: Low-level components of analytic activity in information visualization. IEEE Symposium on Information Visualization, 2005. INFOVIS 2005. pp. 111–117 (2004)
6. Arias-Hernandez, R., Green, T., Fisher, B.: From cognitive amplifiers to cognitive prostheses: Understandings of the material basis of cognition in visual analytics. Interdisciplinary Science Reviews **37**(1), 4–18 (2012)
7. Brown, J., Collins, A., Duguid, P.: Situated cognition and the culture of learning. Educational researcher **18**(1), 32 (1989)
8. Bucy, E.: Interactivity in society: Locating an elusive concept. The Information Society **20**(5), 373–383 (2004)
9. Clark, A.: Microcognition: Philosophy, Cognitive Science, and Parallel Distributed Processing. Explorations in cognitive science. MIT Press (1991)
10. Clark, A.: Time and mind. The Journal of Philosophy **95**(7), 354 (1998)
11. Clark, A.: Supersizing the Mind: Embodiment, Action, and Cognitive Extension. Philosophy of Mind Series. Oxford University Press (2008)
12. Clark, A., Chalmers, D.: The extended mind. Analysis **58**(1), 7–19 (1998)
13. Crystal, A., Ellington, B.: Task analysis and human-computer interaction: Approaches, techniques, and levels of analysis. In: Tenth Americas Conference on Information Systems, pp. 1–9. New York, New York, USA (2004)

14. Dourish, P.: Where The Action Is: The Foundations Of Embodied Interaction. Bradford Books. MIT Press (2004)
15. Downes, E.J., McMillan, S.J.: Defining interactivity: A qualitative identification of key dimensions. New Media & Society **2**(2), 157–179 (2000)
16. Fabrikant, S.I.: Persistent problem in geographic visualization: Evidence of geovis(ual analytics) utility and usefulness. In: ICA Geovis Commission ICC2011, vol. 44, pp. 2009–2011. Paris, France (2011)
17. Fidel, R.: Human Information Interaction: An Ecological Approach to Information Behavior. MIT Press (2012)
18. Funke, J.: Complex problem solving: A case for complex cognition? Cognitive Processing **11**(2), 133–42 (2010)
19. Gotz, D., Zhou, M.: Characterizing users visual analytic activity for insight provenance. IEEE Symposium on VAST pp. 123–130 (2008)
20. Hang, H., Auty, S.: Children playing branded video games: The impact of interactivity on product placement effectiveness. Journal of Consumer Psychology **21**(1), 65–72 (2011)
21. Hannon, J., Atkins, P.: All about interactivity. Tech. rep., Victoria, Australia (2002)
22. Hegarty, M.: The cognitive science of visual-spatial displays: Implications for design. Topics in Cognitive Science **3**(3), 446–474 (2011)
23. Hollan, J., Hutchins, E., Kirsh, D.: Distributed cognition: Toward a new foundation for human-computer interaction research. ACM Transactions on Computer-Human Interaction (TOCHI) **7**(2), 174–196 (2000)
24. Hutchins, E.: Cognition in the Wild. Bradford Books. MIT Press (1995)
25. Hutchins, E., Klausen, T.: Distributed cognition in an airline cockpit. Cognition and Communication at Work pp. 15–34 (1996)
26. Jensen, J.: Interactivity: Tracking a new concept in media and communication studies. Nordicom Review **19**(1), 185–204 (1998)
27. Johnson, C., Moorhead, R., Munzner, T., Pfister, H., Rheingans, P., Yoo, T.: NIH-NSF Visualization Research Challenges. Tech. rep., Los Alamitos, CA (2006)
28. Kaptelinin, V., Nardi, B.: Activity Theory in HCI. Morgan & Claypool Publishers (2012)
29. Keim, D., Kohlhammer, J., Ellis, G.: Mastering The Information Age-Solving Problems with Visual Analytics (2010)
30. Keim, D., Mansmann, F., Schneidewind, J., Thomas, J., Ziegler, H.: Visual analytics: Scope and challenges. In: Visual Data Mining: Theory, Techniques and Tools for Visual Analytics, lncs edn. Springer (2008)
31. Kiousis, S.: Interactivity: a concept explication. New Media & Society **4**(3), 355–383 (2002)
32. Kirsh, D.: Interactivity and multimedia interfaces. Instructional Science **25**(2), 79–96 (1997)
33. Kirsh, D.: Metacognition, distributed cognition and visual design. Cognition, Education, and Communication Technology pp. 1–22 (2005)
34. Kirsh, D.: Problem solving and situated cognition. The Cambridge handbook of situated cognition pp. 264–306 (2009)
35. Kirsh, D., Maglio, P.: On distinguishing epistemic from pragmatic action. Cognitive Science: A Multidisciplinary Journal **18**(4), 513–549 (1994)
36. Knauff, M., Wolf, A.G.: Complex cognition: The science of human reasoning, problem-solving, and decision-making. Cognitive Processing **11**(2), 99–102 (2010)
37. Laine, P., Phil, L.: Explicitness and interactivity. Proceedings of the 1st international symposium on Information and communication technologies p. 426 (2003)
38. Liang, H.N., Parsons, P., Wu, H.C., Sedig, K.: An exploratory study of interactivity in visualization tools: Flow of interaction. Journal of Interactive Learning Research **21**(1), 5–45 (2010)
39. Liang, H.N., Sedig, K.: Can interactive visualization tools engage and support pre-university students in exploring non-trivial mathematical concepts? Computers & Education **54**(4), 972–991 (2010)
40. Liang, H.N., Sedig, K.: Role of interaction in enhancing the epistemic utility of 3D mathematical visualizations. International Journal of Computers for Mathematical Learning **15**(3), 191–224 (2010)

41. Liu, Y., Shrum, L.J.: A dual-process model of interactivity effects. Journal of Advertising **38**(2), 53–68 (2009)
42. Liu, Z., Nersessian, N., Stasko, J.: Distributed cognition as a theoretical framework for information visualization. IEEE transactions on visualization and computer graphics **14**(6), 1173–80 (2008)
43. Liu, Z., Stasko, J.: Mental models, visual reasoning and interaction in information visualization: a top-down perspective. IEEE transactions on visualization and computer graphics **16**(6), 999–1008 (2010)
44. Mann, S.: Conversation as a basis for interactivity. In: Proceedings of the 15th Annual Conference of the National Advisory Committee on Computing Qualifications, pp. 281–288. Hamilton, NZ (2002)
45. Marchionini, G.: Information Concepts: From Books to Cyberspace Identities (2010)
46. McClelland, J.L.: Emergence in cognitive science. Topics in Cognitive Science **2**(4), 751–770 (2010)
47. Mirel, B.: Interaction Design for Complex Problem Solving: Developing Useful and Usable Software. The Morgan Kaufmann Series in Interactive Technologies. Morgan Kaufmann (2004)
48. Nardi, B.: Studying context: A comparison of activity theory, situated action models, and distributed cognition. Context and consciousness: Activity theory and human-computer interaction pp. 69–102 (1996)
49. Parsons, P., Sedig, K.: Common visualizations: Their cognitive utility (this volume)
50. Parsons, P., Sedig, K.: Distribution of information processing while performing complex cognitive activities with visualization tools (this volume)
51. Parsons, P., Sedig, K.: Properties of visual representations: Improving the quality of human-information interaction in complex cognitive activities. Journal of the American Society for Information Science and Technology (under review)
52. Pike, W.a., Stasko, J., Chang, R., OConnell, T.A.: The science of interaction. Information Visualization **8**(4), 263–274 (2009)
53. Pohl, M., Wiltner, S., Miksch, S., Aigner, W., Rind, A.: Analysing interactivity in information visualisation. KI - Künstliche Intelligenz **26**(2), 151–159 (2012)
54. Purchase, H., Andrienko, N., Jankun-Kelly, T., Ward, M.: Theoretical foundations of information visualization. In: A. Kerren, J.T. Stasko, J.D. Fekete, C. North (eds.) Information Visualization: Human-Centered Issues and Perspectives, *Lecture Notes in Computer Science*, vol. 4950, pp. 46–64. Springer Berlin Heidelberg, Berlin, Heidelberg (2008)
55. Scaife, M., Rogers, Y.: External cognition: how do graphical representations work? International Journal of Human-Computer Studies **45**(2), 185–213 (1996)
56. Scholtz, J.: Beyond usability: Evaluation aspects of visual analytic environments. In: IEEE Symposium on Visual Analytics Science and Technology, pp. 145–150 (2006)
57. Sedig, K.: Need for a prescriptive taxonomy of interaction for mathematical cognitive tools. Lecture Notes in Computer Science pp. 1030–1037 (2004)
58. Sedig, K.: From play to thoughtful learning: A design strategy to engage children with mathematical representations. Journal of Computers in Mathematics and Science Teaching **27**(1), 65–101 (2008)
59. Sedig, K., Klawe, M., Westrom, M.: Role of interface manipulation style and scaffolding on cognition and concept learning in learnware. ACM Transactions on Computer-Human Interaction (TOCHI) **8**(1), 34–59 (2001)
60. Sedig, K., Liang, H.N.: Interactivity of visual mathematical representations: Factors affecting learning and cognitive processes. Journal of Interactive Learning Research **17**(2), 179 (2006)
61. Sedig, K., Liang, H.N.: On the design of interactive visual representations: Fitness of interaction. In: C. Seale, J. Montgomerie (eds.) World Conference on Educational Multimedia, Hypermedia and Telecommunications, pp. 999–1006. AACE (2007)
62. Sedig, K., Liang, H.N.: Learner-information interaction: A macro-level framework characterizing visual cognitive tools. Journal of Interactive Learning Research **19**(1), 147–173 (2008)

63. Sedig, K., Parsons, P.: Interaction design for complex cognitive activities with visual representations: A pattern-based approach. AIS Transactions on Human-Computer Interaction (2013, to appear)
64. Sedig, K., Rowhani, S., Liang, H.N.: Designing interfaces that support formation of cognitive maps of transitional processes: an empirical study. Interacting with Computers **17**(4), 419–452 (2005)
65. Sedig, K., Rowhani, S., Morey, J., Liang, H.N.: Application of information visualization techniques to the design of a mathematical mindtool: A usability study. Information Visualization **2**(3), 142–159 (2003)
66. Sedig, K., Sumner, M.: Characterizing interaction with visual mathematical representations. International Journal of Computers for Mathematical Learning **11**(1), 1–55 (2006)
67. Shneiderman, B.: The eyes have it: A task by data type taxonomy. Tech. rep., University of Maryland, College Park (1996)
68. Thomas, J., Cook, K.: Illuminating the path: The research and development agenda for visual analytics. IEEE Press (2005)
69. Ware, C.: Visual Thinking for Design. Morgan Kaufmann Series in Interactive Technologies. Morgan Kaufmann (2008)
70. van Wijk, J.J.: Views on visualization. IEEE transactions on visualization and computer graphics **12**(4), 421–32 (2006)
71. Yi, J., Kang, Y., Stasko, J., Jacko, J.: Toward a deeper understanding of the role of interaction in information visualization. IEEE Transactions on Visualization and Computer Graphics **13**(6), 1224–1231 (2007)
72. Yoo, W.S., Lee, Y., Park, J.: The role of interactivity in e-tailing: Creating value and increasing satisfaction. Journal of Retailing and Consumer Services **17**(2), 89–96 (2010)