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Functional narrative animation as visual feedback for interactions in 3D visualization

Tiemeng Li[1,2] | **Yangyang Zhu[1]**

[1]School of Digital Media & Design Arts, Beijing University of Posts and Telecommunications, Beijing, 100876, China

[2]Beijing Key Laboratory of Network System and Network Culture, Beijing, 100876, China

Correspondence
Tiemeng Li, 264 MailBox, No.10, Xitucheng Road, Haidian District, Beijing 100876, China.
Email: tiemeng2000@gmail.com

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Abstract

Visual feedback can help users understand the function, state, and outcome of a system during the pre-, mid-, and post-interaction phases. Current visual feedback in 3D visualization scenarios takes less account of information transfer in terms of appearance design and dynamic behavior, which results in visual feedback being presented in a more engineered form and conveying simple information. For these issues, we proposed the concept and method of functional narrative animation as visual feedback for interactions in 3D visualization. We also provided a set of Unity-based animation library and a plugin tool for configuring the animations. Finally, through user experiments and interviews, we analyzed the role of functional narrative animation as in the interactive visual feedback for 3D visualizations and make corresponding design recommendations.

KEYWORDS

data visualization, interaction technique, narrative animation, virtual environment, visual feedback

1 | INTRODUCTION

3D visualization has proven to be advantageous in observing data distribution characteristics and clustering structures.[1] Visual feedback is useful in helping users understand interactions in 3D visualization. Most of the current research on visual feedback for interactions in 3D scenes is focused on specific problems (e.g., object selection,[2] interaction guidance,[3] channel performance,[4] etc.), and most of these visual feedback solutions only consider functional utility, are not visually appealing, and convey relatively simple information.

Animation can convey spatio-temporal information through visual design and motion features. In the field of human-computer interaction (HCI), several articles have begun to focus on the introduction of animation principles and narrative methods into interactive animation.[5,6] There is also a large body of work in the field of visualization that focuses on the narrative role of animation.[7] However, research in these areas has only been validated in mobile devices or desktop interaction, and narrative animation in 3D visualization scenarios has yet to be investigated.

To address these issues, we propose the concept of functional narrative animation, and explore the role of narrative animation in illustrating interactive functions. Our contribution focuses on three main points:

1. We explore the design methodology of functional narrative animation in terms of *visual narrative structure* and *visual narrative discourse*. And we use this methodology to provide a Unity-based animation library and animation description standards.

2. Through user experiments and interviews, we compared three scenarios—no feedback, general feedback and narrative feedback—to assess the role of functional narrative animation and make relevant design recommendations.
3. We developed a plugin for configuring visual feedback animations in the Unity platform, which has been validated to support the configuration of animations for visualization systems based on models.

2 | RELATED WORK

2.1 | 3D visualization interaction

3D visualization has been shown to be able to visualize data structures and clustering information.[1] Visualization interaction is the exploration and analysis of data interfaces by humans with the help of computer systems.[8] In 2009, Gotz and Zhou[9] summarized visual interaction into four levels by observing users analyzing data: *tasks*, *sub-tasks*, *actions*, and *events*. The third of these layers is widely used in the field of visualization because of its relative independence and semantic richness. In this article, we have selected some of the interactions in the third level and disentangled and analyzed 3D visualization interactions using the classification method of Jankowski and Hachet[10] (*navigation*, *object selection and manipulation*, *system control*).

2.2 | Visual feedback

In this article, we adopt the view of Bellotti et al.[11] that visual feedback consists of three components: *feedforward*, *real-time feedback*, and *delay-time feedback*.

Feedforward was first introduced to the field of HCI by Djajadiningrat et al.[12] Feedforward can reduce the probability of interaction errors by showing the interaction results in advance or guiding the user's interaction actions.[3]

Real-time feedback occurs during user interaction and helps the user to understand the state of the interaction. Real-time feedback can be further differentiated into *continuous real-time feedback* and *discrete real-time feedback* based on parameter input characteristics. The former is mostly used for continuous and precise operations, while the latter is mostly used to represent the state of the interaction.

Delay-time feedback occurs after the interaction and is used to show the result of the interaction and help the user understand the transition between states.[13]

2.3 | Interactive and narrative animation

Research on interaction animation can be traced back as far as 1990, when Baecker and Small[14] first collated the categories and potential value of animation and noted that animation can help users understand the functionality in a system. In 1993, Chang and Ungar[5] introduced traditional cartoon animation design principles to interactive interfaces for addressing emotional and cognitive issues in interaction. In 2016, Chevalier et al.[7] explored the role that animation plays in the visualizations.

Animation as a visually dominant medium has received extensive attention in the fields of visualization narrative, interactive narrative, and illustrative narrative. In 2010, Segel and Heer[15] summarized visual narrative strategies suggesting that color highlighting and transition animation can be used to guide the user's eye. In 2019, Dong et al.[6] investigated the narrative characteristics of interactive effects in mobile: they analogized elements, interfaces and animation sequences in interaction to characters, environments and plots in narrative and highlighted the micro-event characteristics in interactive narrative. In 2021, Shi et al.[16] summarized the design space of narrative animation in the field of illustration, using the narrative object and the narrative intention as two design dimensions.

3 | VISUAL FEEDBACK IN 3D VISUALIZATION INTERACTION

In visualization interactions, the third level of interactions with semantic meaning (e.g., inspect, brush, etc.) consists of a variety of basic actions (e.g., click, pinch, release, etc.), each for a different type of visual feedback. To clarify their

Object Select   Object Manipulate   System Control

	Query	Inspect	Filter	Change Metaphor	Brush	Sort	Pan/Zoom	Merge/Split	Annotate
DXR	*select mapping* *update view*	*select view* *inspect data*	*select view* *filter data*	*select mapping* *update view*					
IATK	*select mapping* *update view*		*slider manipulate* *select view* *filter data*	*select model* *update view*	*hand shank* *select view*		*select view* *pan/zoom*		
ScatterPlot Cube		*slider manipulate* *select view* *inspect data*		*select filed* *filed manipulate* *update view*	*gesture* *select view*	*select filed* *filed manipulate* *sort view*	*select view* *pan/zoom*		
ImAxes				*select aixes* *aixes manipulate* *update view*			*select view* *pan/zoom*		
Transfer Chord		*select view* *inspect data*	*select view* *filter data*					*select section* *merge/split*	
Chart Accent	*select mapping* *update view*	*select view* *inspect data*		*select model* *update view*	*mouse* *select view*				*select view* *annotate*

FIGURE 1 Interaction analysis of 3D visualization systems

relationship to visual feedback, in this section, we analyze 11 visual interactions on 6 systems and propose a visual feedback framework for 5 different interaction stages.

3.1 | 3D visualization interactive analysis

Our selected systems include: two Unity-based 3D visualization building tools: DXR[17] and IATK,[18] to analyze the query, inspect, filter and changing metaphor interactions. Two immersive visualization analysis platforms: ImAxes[19] and ScatterPlotCube,[20] to analyze interactions on brush, sort, and zoom and pan interactions. And two desktop visualization systems: Transfer Chord[21] and ChartAccent.[22] The former is used to analyze relational data, we used to analyze the merge and split interactions. The latter is used to annotate views, it helps us to analyze the annotate interaction.

As shown in Figure 1, we have split all the 11 interactions according to object selection (blue), object manipulation (green), and system control (yellow). Most of these interactions can be distinguished as object selection + system control (blue + yellow) and object selection + object manipulation (blue + green).

Object selection + system control: The query in DXR, for example, is further split into three parts: select data, select mapping, and update view. In both select data and select mapping interactions, the user needs to align the ray with the option in the menu, which provides discrete real-time feedback (e.g., color highlighting) to inform the user of the selected status of the object.

Update view is executed when the user clicks a button, and until it is executed, the user does not know what will happen, so it is possible to provide a feedforward to predict the outcome of the action in advance. During the process of clicking the update view button, discrete real-time feedback can be used to indicate whether a click was successful or not. Finally, after the user clicks on the button, delay-time feedback can be provided to show the result.

Object selection + object manipulation: An example of this is pan/zoom in IATK. Before the user can pan/zoom a view, the view needs to be selected.

In the select view phase, discrete real-time feedback is provided to inform the user of the selected state. In the pan/zoom phase, the user controls the change of the view in real time by moving the hand, we can providing continuous real-time feedback to show the continuous state of the view.

3.2 | 3D visual feedback framework

In summary, we distinguish the interactions requiring visual feedback into the following five phases: (1) *discrete real-time feedback* for object selection; (2) *continuous real-time feedback* for object manipulation; (3) *feedforward* before system control; (4) *discrete real-time* feedback in system control; (5) *delay-time feedback* after system control.

4 | FUNCTIONAL NARRATIVE ANIMATION

Functional narrative animation is a form of animation that uses a narrative approach to explain the function of interaction. In this article, we focus on visual feedback in 3D visual interactions. Figure 2 shows the production process of functional

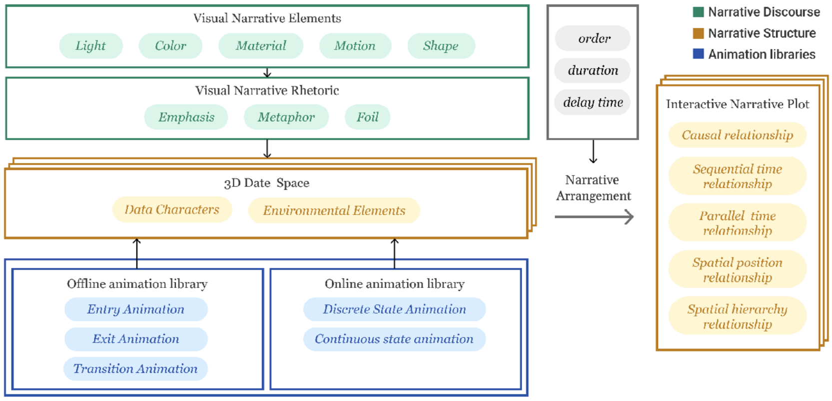

FIGURE 2 Functional narrative animation production pipeline in 3D visualization of interactive scenes: The movement of data characters and environmental elements in 3D data space form animation sequences that are choreographed to form interactive narrative plots.

narrative animation of visual feedback in 3D visualization interactions, including three parts: *visual narrative structure*, *visual narrative discourse*, and *animation library*.

4.1 | Visual narrative structure

The visual narrative structure consists of three parts: *data characters*, *3D data space*, and *interactive narrative plots*.

4.1.1 | Data characters

The data characters can be shaped on three levels: *appearance*, *movement*, and *character definition*.

Appearance: Similar to the character's external features in a narrative. In 3D scenes, we can shape data characters by combining colors, shapes, materials, and light effects.

Movement: Similar to the depiction of character behavior in a narrative. During interaction, the data character needs to respond to the user's input. After the interaction, the movement of the data character also needs to match the user's perception, for example, by providing a slow-in and slow-out animation curve.

Character definition: We distinguish data characters into primary and secondary roles based on the focus of the user's attention. The primary role is highlighted and the secondary role supports the movement of the primary role. It is also possible to distinguish between entry roles, exit roles, and transition roles based on the disappearance of the appearance and movement of data characters.

4.1.2 | 3D data space

In 3D visualization interaction, the environment is the space in which the data character is carried, specifically in the form of axes, grids, and scales. These environment elements are affected by user interaction in the same way as the data characters, and the movement of the data characters also causes changes to the environment elements.

4.1.3 | Interactive narrative plots

In this paper, we argue that the movement of interaction-driven data characters in a visualization environment constitutes a basic sequence of events, and that the choreographed combination of these movements can constitute a narrative plot in a visualization interaction. (As shown in the orange section of Figure 2, specific narrative relationships and examples are shown in Table 1.)

TABLE 1 Interactive narrative relationships in 3D visualization interactions

Relationship	Cases
Causal	*Filtering*: Selecting data causes it to disappear
Sequential time	*Query*: First displacement, then scaling, finally color change
Parallel time	*Brush*: Brush area and data change color at the same time
Spatial position	*Sort*: The data changes position after the execution of the command
Spatial hierarchy	*Inspect*: Data information appears in the vicinity of the data

4.2 | Visual narrative discourse

4.2.1 | Visual narrative elements

Visual elements with perceived affordance can be used as *visual narrative elements* in a 3D scene, which we will group into five basic elements: *light*, *materials*, *color*, *shape*, and *motion*. Using *visual narrative rhetoric*, we combine these elements to form data characters and environmental elements in functional narrative animations (as shown in green in Figure 2).

4.2.2 | Visual narrative rhetoric

In 3D visualization interactive narrative, we narrate through dynamic visual elements. The following three main types of rhetoric are used.

Emphasis refers to highlighting a particular feature of something. In 3D visualization interactions, to draw the user's attention, we use light effects, color changes, and so forth to emphasize the occurrence of such changes before an object moves or when its state changes.

Metaphor help users quickly understand unfamiliar interactions by associating source and target domains. For example, we use the metaphor of bubbles to describe the space around the data, telling the user the distance between their fingertips and the data as they approach the data point.

Foil is the process of describing something while at the same time describing something else that is related to it to enhance the description. For example, after modifying the dimensional coordinates, we show the scale change of the axes while the data is displaced to underline the movement of the data.

4.3 | Animation library

We have built a library of functional narrative animations in Unity and the library currently contains 21 animations (shown in Figure 3): 13 offline animations (for delay-time feedback) and 8 online animations (for real-time feedback).

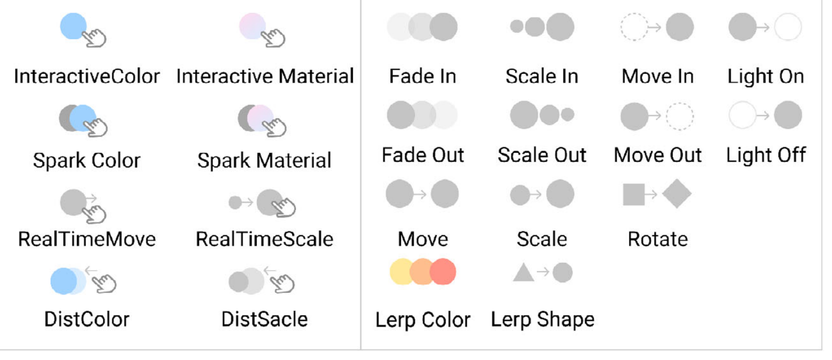

FIGURE 3 Animation library (online animations left, offline animations right)

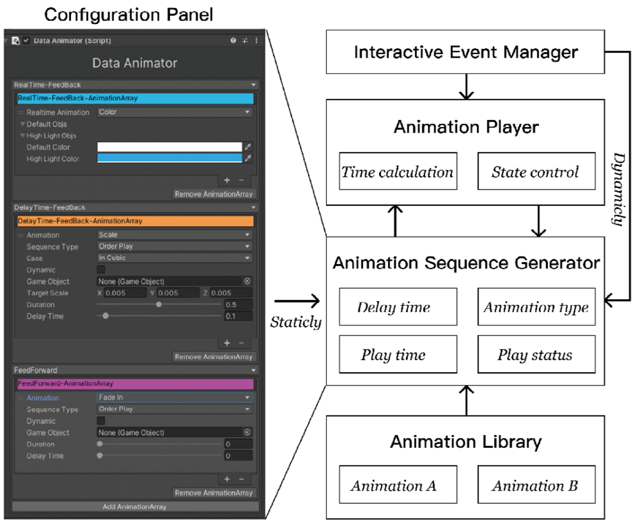

FIGURE 4 Architecture and pipeline of data animator plugin

5 | ANIMATION PLUGIN

The plugin consists of five main parts: *configuration panel*, *animation sequence generator*, *animation player*, *interaction event manager*, and *animation library* (as shown in Figure 4).

The plugin is used by first configuring the basic parameters of the animation in the *configuration panel* (e.g., animation type, feedback type, playback sequence, delay time, etc.) and then dynamically passing other dynamic parameters in the *interaction event manager*. These parameters are then matched in the *animation sequence generator* to the animations in the *animation library* and finally played by the *animation player* (as shown in Figure 4 right).

6 | CASES AND EVALUATION

6.1 | Cases

We have configured three cases of interactive visual feedback in Unity based on DXR[17]: delay-time feedback in query, real-time feedback in brush, and feedforward in inspect. A control group of two (no feedback and general feedback) and an experimental group (narrative feedback) were created separately for each case and used for the subsequent evaluation.

In the query: The user is asked to toggle the data dimensions of the X, Y, and Z axes, and we providing delay-time feedback after clicking the UpdateVis button. The narrative feedback group uses emphasis (motion lighting effects, easing in and out curves) and foil rhetoric (scaling of axis scales) to describe changes in the view (e.g., Figure 5a1). General feedback provides only linear displacement of data points (e.g., Figure 5a2); and no feedback does not provide view transitions (e.g., Figure 5a3). *In the brush*: the user can drag a slider on an axis to slect the data in the view, and we provide real-time feedback during this process. The narrative deedback group uses the rhetorial techniques of metaphor (ice cube metaphor) and emphasis (highlighting light effect, blinking light effect) to highlight the selected data (e.g. Figure 5b1). General feedback group in which the box is provided and the unchecked data is diminished (e.g. Figure 5b2). And no feedback group in which only the box is provided and the data dose not change (e.g. Figure 5b3).

In the inspect, the data details pop up when the user touches the data. We provide the feedforward before the user touches the data. The narrative feedback group uses the rhetorical techniques of metaphor (bubble metaphor) and emphasis (highlighting effect) to describe the change when the user approaches the data (e.g., Figure 5c1). The general feedback

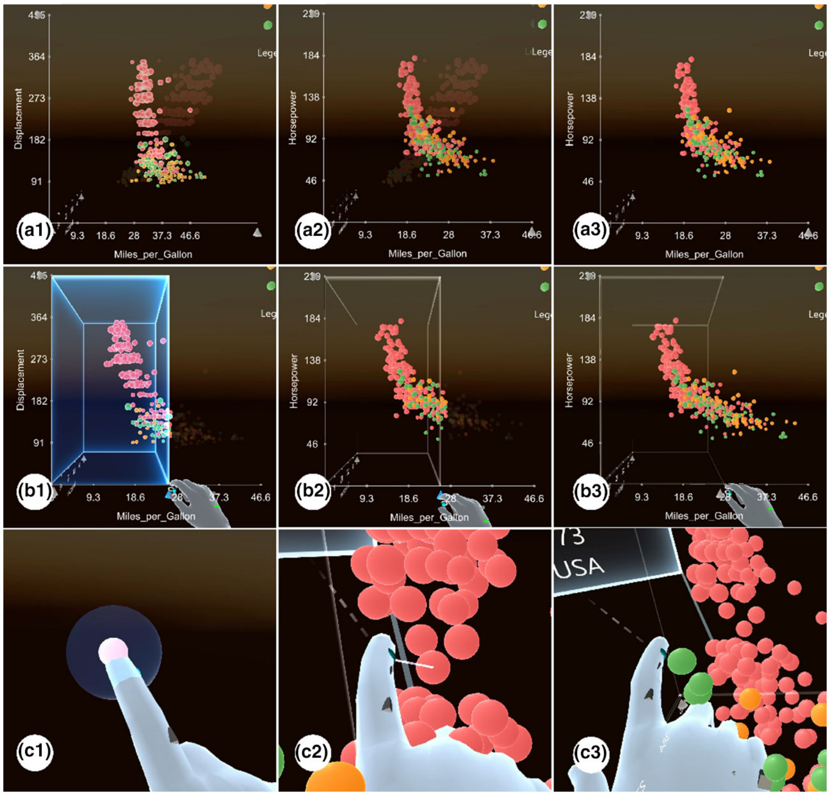

FIGURE 5 (a1, b1, c1) Narrative feedback group, (a2, v2, c2) general feedback group, and (a3, b3, c3) no feedback group

group has a white line attached to the data when approached (e.g., Figure 5c2); no feedback group provides no feedforward (e.g., Figure 5c3).

6.2 | Evaluation

In this section, we set up a set of controlled experiments to assess the role of functional narrative animation in the visual feedback of 3D visualizations and through questionnaires and interviews to understand user's subjective evaluation of the functional narrative animation.

6.2.1 | Design

We recorded five metrics in the experiment: 1 objective metric (*completion time*) and four subjective metrics (*comprehensibility*, *ease of use*, *usability* and *visual comfort*).

The user is invited to find a specific data point in the view (which is described by three dimensions and a color attribute) by using three interactions—query, brush, and inspect—and to record the user's *completion time*. Each set of tasks is continuous and the user can switch the order between the three interactions at will.

At the end of the experiment, users were invited to evaluate the three control groups independently on four indicators. Each experimental group addressed a total of 12 questions on 3 interactions, with scores ranging from 1 to 5. After completing the evaluation, users were invited to experience the other two control groups and to rank their preferences.

6.2.2 | Hypothesis

Prior to the experiment, we made the following assumptions:

(H1) The narrative feedback group would take less time to complete than the no-feedback group and be on par with the general feedback group.
(H2) The narrative feedback group would outperform the no-feedback group in comprehensibility and be on par with the general feedback group.
(H3) The narrative feedback group outperformed the no-feedback group in terms of ease of use and was on par with the general feedback group.
(H4) The narrative feedback group outperformed the no-feedback group in terms of usability and was on par with the general feedback group.
(H5) The narrative feedback group outperformed the other two groups in terms of visual comfort.
(H6) The narrative feedback group outperformed the other two groups in the ranking of user likeability.

6.2.3 | Apparatus and Users

The experimental device was an Oculus Rift VR kit running on a Windows desktop (CPU: i5-9400F 2.9 GHz, RAM: 32 GB, GPU: GTX 1060 6 GB). A total of 36 users were invited to participate, 18 of whom had experience with desktop-based visualization systems and 4 with immersive visualization systems. These users were between 21 and 26 years old, and we randomly assigned these 36 people to 3 control groups, with 12 people guaranteed in each group.

6.2.4 | Results

The result of experiment is shown in Figure 6.

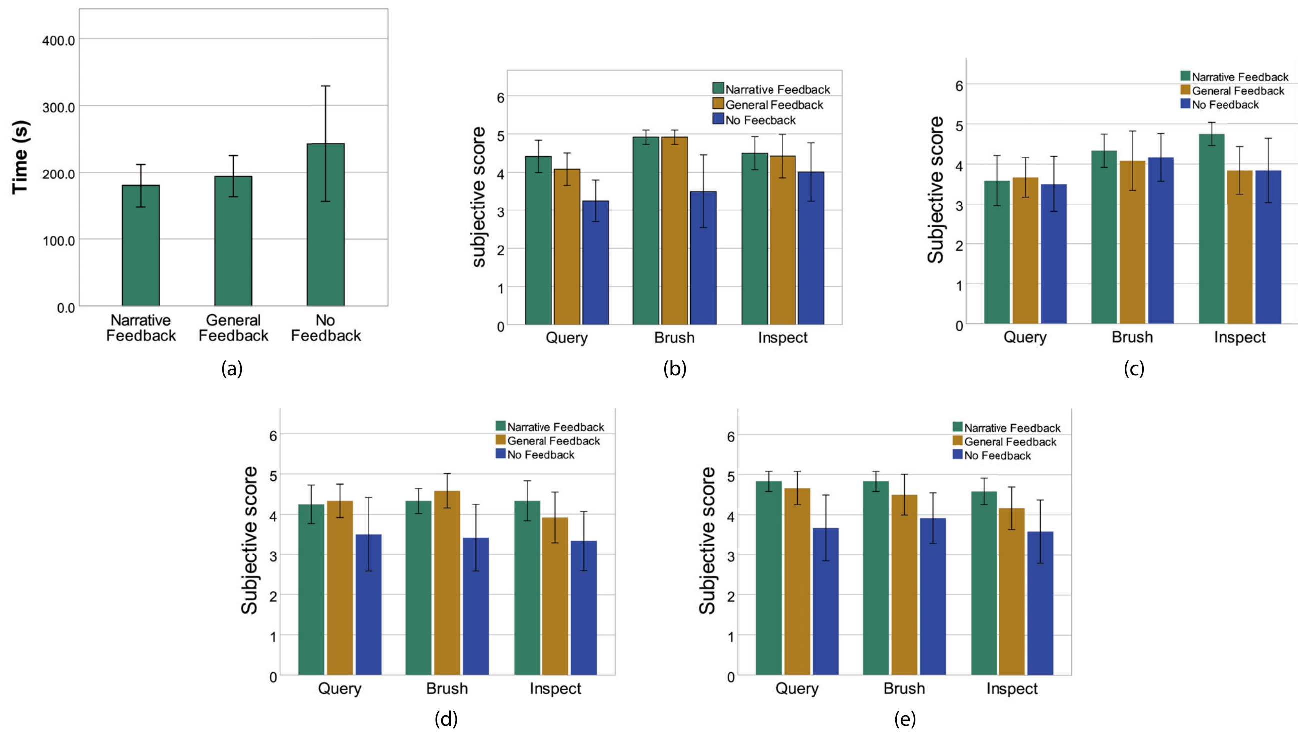

FIGURE 6 Results of evaluation. (a) Average task completion time, (b) comprehensibility score, (c) ease of use score, (d) usability score, and (e) visual comfort score

1. **There were no significant differences in task completion times between the three control groups** (Figure 6a): The no-feedback group took the longest mean time and the narrative feedback group the shortest (no feedback/narrative feedback: $p = .147 > .05$, general feedback/narrative feedback: $p = .488 > 0.05$), so hypothesis H1 was rejected.
2. **In terms of comprehensibility, the narrative feedback group was better than the no-feedback group for both query and brush** (Figure 6a): (query: $p = .001 < .05$, brush: $p = .008 < .05$) and was not significantly different compared to the general feedback group, assuming that H2 could be partially accepted.
3. **In terms of ease of use, narrative feedback in the inspect was superior to the other two groups** (Figure 6b): (no feedback/narrative feedback: $p = .034 < .050$; general feedback/narrative feedback: $p = .006 < .050$), assuming partial acceptance of H3.
4. **In terms of usability, narrative feedback in brush and inspect was superior to the no-feedback group** (Figure 6c): (brush: $p = .040 < .050$; inspect: $p = .021 < .050$) and was not significantly different compared to general feedback, assuming that H4 could be partially accepted.
5. **In terms of visual comfort, the narrative feedback group outperformed the no-feedback group in all three interactions** (Figure 6d): (query: $p = .011 < .050$; brush: $p = .010 < .050$; inspect: $p = .021 < .050$), with no significant difference compared to the general feedback group, assuming that H5 was partially accepted.
6. **Almost all users ranked the narrative feedback group first** (Figure 6d): In the post-questionnaire experience and interviews, 34 users ranked narrative feedback first and two others ranked narrative feedback alongside general feedback, so it is assumed that the H6 is acceptable. The majority of users described the narrative feedback group as interesting and engaging and felt that the narrative feedback provided more information and that the organization of the information was more intuitive and vivid. A small number of users felt that the narrative feedback was functionally consistent with the general feedback and that some elements may be redundant. One expert user suggested that narrative feedback may not be suitable for rigorous analytical scenarios, but is more appropriate for use in the business world.

7 | DISCUSSION

In the comparison of the three groups of feedback solutions, narrative feedback showed varying degrees of strengths and limitations in objective indicators (completion time), subjective indicators (*comprehensibility*, *ease of use*, *usability*, and *visual comfort*) and in the ranking of liking.

In terms of task completion time, although the three feedback schemes did not show significant differences, the errors in the narrative feedback and general feedback groups were smaller than in the no-feedback group. This may be related to the absence of feedback, where users were unable to interact consistently with feedback in the no-feedback group, a situation that was partially improved in the other two groups.

The narrative feedback group showed a clear advantage over the no-feedback group on the four subjective indicators. But this advantage was not significant when compared to the general feedback. In the user interviews, some users noted that although the narrative feedback was more interesting and engaging in its presentation than the general feedback, the general feedback was also able to help him complete the task. This may indicate that there is no fundamental difference between general feedback and narrative feedback in terms of helping users understand the interaction, adjusting the interaction actions and achieving the purpose of the interaction.

However, in terms of user liking, narrative feedback was widely welcomed, with most users citing the more obvious and intuitive form of narrative feedback, its ability to convey more detail, and its more elegant and natural presentation. This may suggest that providing some interesting and formally rich feedback, alongside meeting functional requirements, can help users to enjoy the interaction more. However, it is also important to note that the primary role of functional narrative animation is to illustrate the interaction function, and overly redundant design may also cause discomfort to users.

8 | CONCLUSION

In this article, we design functional narrative animations in 3D visual interactive visual feedback and provide a set of animation libraries and plugins for configuring visual feedback animations. Finally, a set of experiments was conducted to evaluate the role of functional narrative animation in 3D visual interactive visual feedback. The results show that functional narrative animation helps to improve user perception and interaction efficiency in interactions and is preferred by most users.

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ORCID

Tiemeng Li https://orcid.org/0000-0001-5507-0397
Yangyang Zhu https://orcid.org/0000-0003-4290-6962

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AUTHOR BIOGRAPHIES

Tiemeng Li received his PhD degree in Mechanical Electronic Engineering from Beijing University of Posts and Telecommunications (BUPT) at 2011. Currently, he is an associate professor in School of Digital Media & Design Arts of BUPT. His current research interest includes: Data visualization and visual analytics, immersive user interface, and natural human interaction.

Yangyang Zhu recieved his MS degree in Art from School of Digital Media & Design Arts, Beijing University of Posts and Telecommunications at 2022.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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