VR's Frames of Reference: A Visualization Technique for Mastering Abstract Multidimensional Information

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ABSTRACT

This paper describes a research study that investigated how designers can use frames of reference (egocentric, exocentric, and a combination of the two) to support the mastery of abstract multidimensional information. The primary focus of this study was the relationship between FORs and mastery; the secondary focus was on other factors (individual characteristics and interaction experience) that were likely to influence the relationship between FORs and mastery. This study's outcomes (1) clarify how FORs work in conjunction with other factors in shaping mastery, (2) highlight strengths and weaknesses of different FORs, (3) demonstrate the benefits of providing multiple FORs, and (4) provide the basis for our recommendations to HCI researchers and designers.

Keywords

Virtual reality, visualization, interaction design, visual design, education applications

INTRODUCTION

In today's knowledge-based society, the ability to visualize and manipulate abstract and multidimensional information is crucial for communicating and understanding ideas [5, 14]. Whether working in scientific, environmental, political, or even social domains, people frequently find themselves trying to visualize complex information. They use visualization techniques such as graphically representing information, adopting different frames of reference, imagining how information changes over time, etc. to help with this task [9, 10].

A testament to the power of visualization lays in the history of scientific discovery. Many of our great scientists (e.g., Albert Einstein, August Kekulé, and James Watson) made conceptual leaps by visualizing abstract phenomena [14]. For example, Einstein's ability to imagine what it would be like to ride on a beam of light gave him insights into his theory of relativity. Unfortunately, the visualization abilities of these scientists are extraordinary - visualization is difficult for most people [5, 18]. Thus, techniques that can help people recognize patterns, reason qualitatively about physical processes, translate among frames of reference, and envision dynamic models are important.

In the area of graphic design and HCI, considerable attention has been given to the development of visualization techniques to support these processes [e.g., 6, 17]. The goal in using visualization techniques is to enable people to rely on their perceptual abilities when looking for patterns and relationships in information. McCormick, DeFanti, and Brown [10] provide an elegant description of what designers are trying to achieve through visualization:

> "Visualization ... transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations. Visualization offers a method for seeing the unseen. It enriches the process of scientific discovery and fosters profound and unexpected insights."

Although visualization techniques can be powerful, they can also be confusing or misleading. Our everyday experiences demonstrate this. Take graphical interaction plots (the kind of graph used in the *Results & Discussion* section) as an example. Most likely you can remember instances in which such graphs clarified a complex set of interactions and other instances in which the graphs were either too complex to comprehend or very misleading (e.g., because the scale of the graph exaggerated minor differences). As this simple example illustrates, the visualization techniques that designers employ can be powerfully enlightening or they can be seriously deceptive. Therefore, investigating major types of visualization techniques to identify their strengths and weaknesses is essential to the HCI research agenda. Through careful research, we help designers understand how to use these techniques to support communication and mastery.

One common visualization technique - frames of reference (FORs) - warrants such investigation. Designers of visualization environments often use FORs, or different perspectives, in an attempt to highlight patterns and

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important relationships. Although there are numerous FORs, many can be classified as exocentric or egocentric. The *exocentric FOR* provides a view of an environment or phenomena from the outside, while *the egocentric FOR* provides a view from within. In this paper, we are concerned with these two FORs, as well as with a third FOR that we call the *bicentric FOR.* The bicentric FOR is a visualization technique in which users alternate between the egocentric and exocentric FORs.

Lessons from Previous Research on FORs

A review of the literature indicates that more research on FORs can be used for visualization is needed. It also underscores the importance of examining FORs within the context of factors such as individual characteristics and interaction experiences.

Studies to date have not examined how FORs can be used to support the mastery of complex and abstract information. These studies have focused primarily on navigational performance and spatial learning. Nevertheless, this body of research provides insights into important issues to consider. First, it is important to examine performance during the learning process as well as mastery outcomes. Prior research shows that FORs can affect how people perform in an environment as well as what they learn from their experiences [13, 16]. Second, we need to explore how well different FORs support the learning of different kinds of information. Specifically, prior research suggests that the exocentric view might help people notice global information (general trends in the data) and that the egocentric view can help people notice local information (or details about that information) [e.g., 2, 11, 19]. Third, we need to consider the environment in which people are asked to apply their knowledge. Prior research indicates that translating between FORs can be difficult, making it easier for someone to answer questions from the FOR in which they learned than from an alternative FOR [1].

Finally, we need to consider the role external factors such as individual characteristics and interaction experiences play in shaping the relationship between FORs and mastery. Individual differences research suggests that characteristics such as gender, spatial ability and domain experience can affect how adept people are with visualization tools [12] and their aptitudes for mastering abstract information [7]. Additionally, dimensions of the interaction experience (e.g., usability, simulator sickness, motivation, and presence) can facilitate or hinder the task, in this case to master abstract information.

Research Goals & Hypotheses

We designed this study to address the following research questions: (1) how do FORs influence mastery?, and (2) how do other factors (i.e., individual characteristics and interaction experience) influence the relationship between FORs and mastery?

Figure 1 summarizes how we expected the FORs of a visualization environment to work with the other factors to shape the learning process and mastery outcomes. Frames of reference influence mastery. The effectiveness of FORs depends on the concept being learned and the environment in which people have to apply their knowledge. Individual characteristics (e.g., gender, spatial ability, domain experience, etc.) influence mastery and potentially moderate the relationship between FORs and mastery. Dimensions of the interaction experience (e.g., usability, motivation, simulator sickness, etc.) mediate the relationship between FORs and mastery (to be affected by FORs and, in turn, to influence mastery).

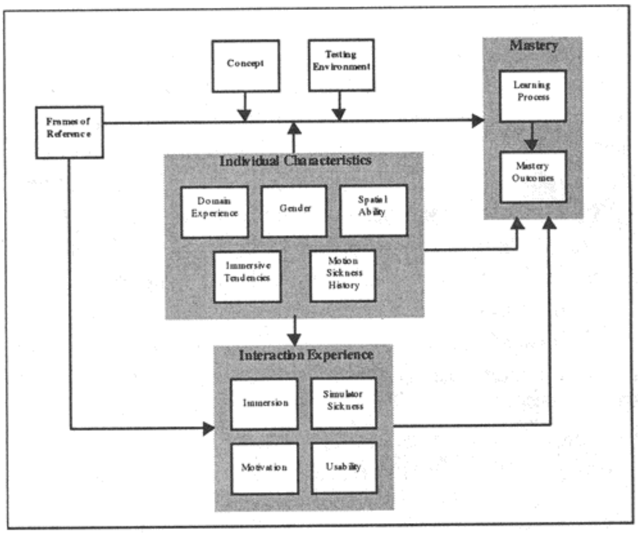

Figure 1. A hypothetical model describing how FORs and other factors work together to influence mastery outcomes.

METHODS

Participants

Forty-eight students, 30 males and 18 females, completed the study. Participants were juniors and seniors in advanced physics classes at a local high school. None were familiar with the concepts covered in this study.

Design

The general design of this study was a mixed 3 (FOR group, between) x 2 (force-motion or FM concept, within) x 2 (descriptive-causal or DC concept, within) factorial design. The three FOR groups were egocentric, exocentric, and bicentric (alternating between egocentric and exocentric FORs). Participants were assigned randomly to a FOR group such that groups were proportionally balanced on gender.

After providing background information, students learned about electric fields via a visualization environment that supported the FOR to which they were assigned. They were asked to master *descriptive* (definitions and representations) and *causal* (rules explaining relationships) information concerning *force* (the distribution of force in electric fields) and *motion* (how test charges are propelled by forces in electric fields). Approximately 3 days after completing the lessons, students participated in a testing session, during which their mastery of the concepts was assessed.

Independent measures & materials

Visualization environment

The environment used in this study was MaxwellWorld (MW), an immersive VR visualization environment that was developed by Project ScienceSpace [3]. MW was designed to help students master a complex and abstract domain of science - electric fields. In very simple terms, an electric field represents the distribution of force that a standard charged particle (a test charge) would have at any point throughout a space surrounding charged particles.

MW allowed students to build electric fields by placing charged particles (source charges) in a three-dimensional space. Students could then manipulate abstract and multidimensional representations of the electric field. These representations (e.g., test charge traces, and field lines, and moving test charges with path markers) provided information about the distribution of force in the electric field and how a charged particle would move if it were released in the electric field. Figure 2 illustrates MW's interface and representations.

MW's physical interface was typical of current high-end virtual reality. Hardware included a Silicon Graphics Onyx Reality Engine2 graphics workstation, a Silicon Graphics Indy workstation, Virtual Research's VR4 headmounted display (HMD), a 3Ball, menu device, and Polhemus magnetic tracking system. The workstations were used to create the sounds and graphics used in MW. The remaining equipment enabled the user to interact with MW. On his or her head, the user wore the HMD. In one hand, the user held the 3-ball, which was represented in MW as a virtual hand. In the other hand, he or she held menu device, which was represented in MW as a hand holding a menu system (Figure 3). The Polhemus tracking system monitored the location of the HMD, the 3Ball, and the menu device. This enabled the user to control where he or she was looking and to use the virtual hand, menus, and direct manipulation to perform tasks in MW.

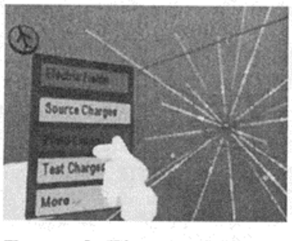

Figure 2. The virtual hand and menus with an electric field in the background.

Figure 3. A person interacting with MW.

FOR group

Students interacted with MW from one of three FORs: egocentric, exocentric, and bicentric. In the exocentric FOR, students explored electric fields from a distance. In the egocentric FOR, students explored electric fields as a test charge immersed within the fields. In the bicentric FOR, students alternated between the egocentric and exocentric FORs for successive learning activities.

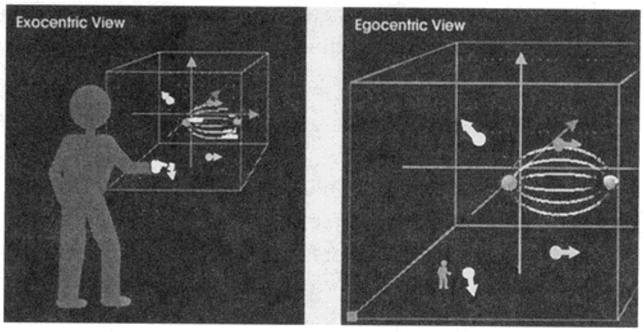

Figure 4. Egocentric and exocentric FORs in MW.

Lessons

Scripted lessons served to guide participants through the learning process and to structure their inquiries about force and motion while using MW. Lessons were administered verbally to one student at a time. They consisted of a series of learning activities; each learning activity consisted of a cycle of predictions and observations. Thus, participants began each activity by making a verbal prediction about the outcomes of that activity; they then tested their predictions; finally, they discussed their observations.

Lessons focused on electric field concepts. Note that the electric field domain was deemed appropriate for investigating how FORs influence mastery of abstract multidimensional information for several reasons. First, the principles underlying the phenomena are abstract and multidimensional. Thus, mastery of electric fields requires students to perform typical visualization tasks: to work with abstract concepts, imagine how changes to source charges change the field, and to recognize and understand patterns in electric field representations. Second, prior research with students studying electric fields demonstrated that they have trouble mastering electric field concepts [3]. Third, some electric field concepts rely primarily on global relationships and others depend more on local relationships.

Concepts being learned – FM concept & DC concept

Students studied two electric field concepts (FM concept): (1) the distribution of force in electric fields, and (2) the motion of test charges through electric fields. Their lessons covered two types of information (DC concept): descriptive (symbolic, or *what,* information = definitions, representations) and causal (conceptual, or ***why***, information = how concepts are organized, rules to explain relationships) [151. To learn about *force,* students studied how forces were distributed in simple and complex electric fields, observed how changes to the electric field affected the distribution of force, and tried to apply rules of superposition (the addition of forces) to explain the distribution of force. To learn about *motion,* students explored how test charges (imaginary charged particles) were propelled by the forces in electric fields (the speed and path they would follow). The concepts of force and motion were selected because an analysis of these concepts suggested understanding force depends more heavily on global than local judgments and that understanding motion requires more local than global judgments.

Dependent measures & materials

Learning process

Participant comments (predictions and observations) provided the basis for monitoring the learning process. Comments for each learning activity were logged during the lessons. Six activities (two at the beginning, middle, and end of the lesson) for force and for motion had synthesis questions asking students to try to summarize key concepts.

Mastery

The mastery test was a transfer test, administered outside of the VR environment. It was developed and refined based on the outcomes of several pilot tests and the expertise of two physics teachers. The test consisted of several kinds of questions: concepts, sketches, and demonstrations. Further, each question had two parts: a *descriptive* component, requiring the student to describe a phenomena; and *causal* component, asking students to explain their responses.

Concepts and sketches were administered via a paper and pencil test. Concepts required students to imagine a force or motion scenario, determine whether it could be true, and explain why; sketches had students use the information presented in a sketch to answer questions about the distribution of force or the motion of a test charge within it. The demonstrations were administered verbally using three-dimensional manipulatives and required students to explore electric fields and demonstrate the distribution of force or the motion of a test charge within them.

Test environment

The test environment was manipulated during the mastery test's demonstrations. All students completed both ego-referenced and exo-referenced demonstrations. For exo-referenced demonstrations, the electric fields were built on a desktop using small manipulatives. For ego-referenced demonstrations, the electric fields were built around the student using larger manipulatives. Thus, students were outside the electric fields for the exo-referenced demonstrations of the test and immersed within the electric fields for the ego-referenced demonstrations, mimicking the exocentric and egocentric FORs in MW.

Individual Characteristics

Individual characteristics included gender, domain experience (science and computers), spatial ability (spatial patterns and spatial visualization), immersive tendencies, and motion sickness history. ETS's CS-2 and VZ-2 [4] were used to measure the two dimensions of spatial ability. Singer & Witmer's [20] Immersive Tendencies Questionnaire and Kennedy et al's [8] Motion Sickness History were used to assess each participant's propensity towards immersion and sickness.

Interaction Experience

Immersion, simulator sickness, usability, and motivation were measured. Singer & Witmer's [20] Presence Questionnaire and Kennedy et al's [8] Simulator Sickness Questionnaire were used to assess how immersed participants were and how they felt physically when using MW. Performance-based usability was assessed via task time and problem rates. Subjective usability and motivation were assessed via 7 point anchored rating scales.

RESULTS & DISCUSSION

How do FORs influence mastery?

Mean mastery scores for each group are shown in Table 1. To determine whether FORs influenced mastery and whether the effectiveness of a FOR depended on the concept being learned or test environment, we conducted two mixed 3 x 2 x 2 analyses of variance (ANOVAs). We also examined learning process data.

Mastery score	**FOR group**		
	Egocentric	**Exocentric**	**Bicentric**
Force	**.636 (.139)**	**.636 (.134)**	**.733 (.109)**
Descriptive	.742 (.113)	.745 (.137)	.811 (.093)
Causal	.525 (.176)	.528 (.149)	.643 (.129)
Ego-referenced*	.632 (.173)	.583 (.216)	.739 (.164)
Exo-referenced*	.587 (.178)	.666 (.157)	.744 (.154)
Motion	**.556 (.160)**	**.494 (.142)**	**.651 (.112)**
Descriptive	.644 (.148)	.601 (.135)	.733 (.084)
Causal	.469 (.179)	.387 (.156)	.568 (.174)
Ego-referenced*	.582 (.193)	.440 (.179)	.708 (.175)
Exo-referenced*	.571 (.178)	.496 (.193)	.623 (.142)

Table 1. Mean mastery scores across FOR groups. * Means are based on the demonstrations only.

The first ANOVA (FOR group by FM concept by DC concept) enabled us (1) to compare overall performance across the groups and (2) to determine whether the groups differed in the extent to which they mastered different kinds of information (FM concept = force vs. motion; DC concept = descriptive vs. causal).

As illustrated in Figure 5, there were significant main effects for FOR group (F_{grp} (2, 45) = 4.64, p = .01), FM concept (F_{fm} (1, 45) = 32.33, p = .0001) and DC concept (F_{dc} (1, 45) = 420.36, p = .0001). There were no significant interactions. Of central interest to us were the main effect for FOR group and the lack of interactions. These two outcomes suggested that the FOR students used in MW influenced mastery outcomes but that the FORs did not differentially affect how well students mastered force and motion or descriptive (what) and causal (why) information.

Two planned comparisons helped to clarify how the groups performed relative to one another. The first contrasted the egocentric and exocentric groups to determine whether students learned more from the egocentric or exocentric FOR. It showed that overall mastery scores for these two FOR groups were not statistically different ($F_{ego\text{-}vs\text{-}exo}$ (1, 45) = .53, p = .47). The second compared the mastery scores for the egocentric and exocentric groups to the mastery scores for the bicentric group. Students benefited more by learning via a combination of FORs than via one of the single FORs ($F_{\text{single-vs-bi}}$ (1, 45) = 9.20, p = .004).

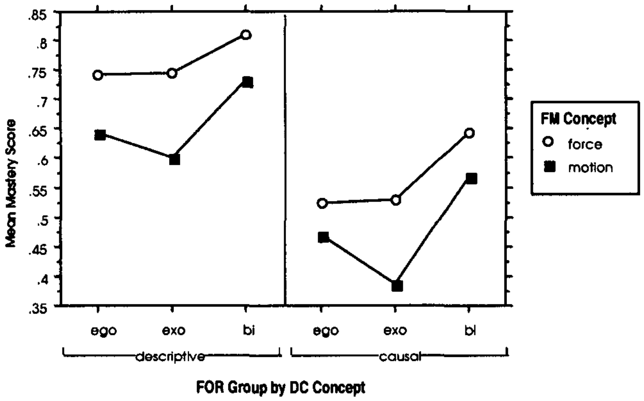

Figure 5. Mastery scores for different concepts.

Learning process data yielded further insights into the FORs. The accuracy and content of predictions, observations, and synthesis questions provided evidence that students in different groups noticed different kinds of information. For example, students in the exocentric group appeared to be more focused on global aspects of the field than on local ones. Accuracy on synthesis questions demonstrated that the superior performance of the bicentric group evolved over time and that this group was slightly more successful in remediating their misconceptions about force and motion than other groups. Finally, mean accuracy during the lessons was highly and positively correlated with mastery outcomes (r (48) = .71, p = .0001).

The second ANOVA (FOR group by FM concept by test environment) focused on demonstration outcomes. It enabled us examine whether the FOR groups differed in the extent to which they were able to adopt different FORs when problem solving (test environment = ego-referenced vs. exo-referenced). Thus, our focus concerned test environment effects. There was not a main effect for test environment. Overall performance (collapsed across FOR groups) on the ego-referenced and exo-referenced portions of the test were roughly equivalent. However, there was a significant FOR group by test environment interaction ($F_{\text{grp*tstenv}}$ (2, 45) = 22.91, p = .0001). Relative performance of the groups varied as a function of the test environment.

An examination of simple effects within each group (comparing ego- and exo-referenced performance) helped to clarify the FOR group by test environment interaction. The exocentric group's ego-referenced scores were significantly lower (-.070) than their exo-referenced scores ($F_{\text{testenv@ego}}$ (1, 15) = 9.53, p = .01). The reverse was true of egocentric and bicentric groups (+.028 and +.039 respectively), although this difference was significant only for the bicentric group ($F_{\text{tstenv@bi}}$ (1, 15) = 5.96, p = .03). To summarize, the exocentric group had trouble working in the ego-referenced environment while the other groups did not and the other groups did not have trouble translating to the exo-referenced environment, always doing at least as well as or better than the exocentric group.

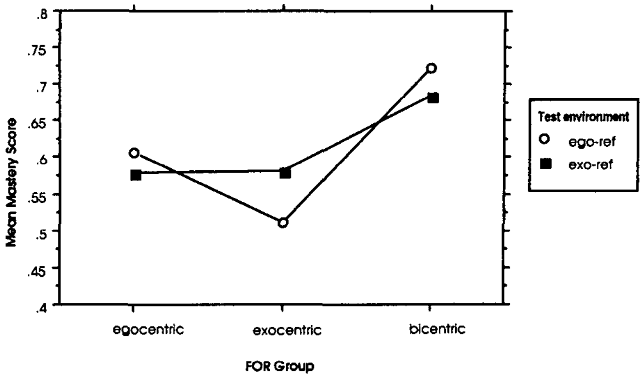

Figure 6. Mastery scores in different testing environments.

How do other factors influence the FOR-mastery relationship?

Both individual characteristics and interaction experiences played important roles in shaping mastery. Individual characteristics explained 23.4% of the variability in mastery scores (R^2 = .234, F (4, 44) = 3.28, p = .02). Gender played the largest role in predicting mastery, with males outperforming females (β_{gender} = .44, t = 3.05, p = .004). Spatial ability (a linear composite of the CS-2 and VZ-2 test scores was used here) was marginally predictive of mastery (β_{spat} = .26, t = 1.85, p = .07). Finally, one aspect of domain experience, total science classes, was predictive of mastery (β_{sci} = -.30, t = -2.03, p = .05); while the other, hours per week using computers, was not. Somewhat counterintuitive, people with domain experience (i.e., more science classes) tended to do more poorly on the mastery test.

To determine whether the effects of FORs varied as a function of individual characteristics, we examined the interaction between individual characteristics and FOR group. Via hierarchical regression, we found none of the interactions to be significant. Thus, the effect of FORs on mastery did not vary as a function of gender, spatial ability, or domain experience.

Interaction experiences explained 30.1% of the variance in mastery scores (R^2 = .301, F (6, 41) = 2.382, p = .017). Task time and simulator sickness were the strongest predictors (β_{time} = -.369, t = -2.645, p = .012; β_{sick} = -.333, t = -2.174, p = .036). As expected, higher simulator sickness resulted in lower mastery; longer task times were also associated with poorer performance on the mastery test. Other measures of usability, immersion, and motivation were not significant predictors of mastery.

In this study, there was high variability in the interaction experiences that could not be attributed to the FORs. In fact a MANOVA showed that FOR group did not significantly predict usability, simulator sickness, immersion and motivation (Wilks Λ = .742, F(12, 80) = 1.17, p = .32). Instead, some aspects of the interaction experience appeared to differ as a function of individual characteristics. For example, spatial ability and domain experience were significant predictors of one aspect of usability - task time ($R^2 = .234$, $F(3, 44) = 4.60$, $p = .004$). Higher domain experience and spatial ability enabled users to complete the lessons more efficiently. Spatial ability was also predictive of simulator sickness; students with higher spatial ability scores experienced fewer simulator sickness symptoms.

Looking at the big picture

Figure 7 illustrates key relationships in this study:

- The bicentric group did better during the learning process and on the mastery test than the other groups.
- The role of concept deserves further investigation. During the lessons, the FORs seemed to highlight different information, but these differences did not result in differential mastery of the concepts.
- People who had been exposed to the egocentric FOR (the egocentric and bicentric groups) performed well in the ego-referenced and exo-referenced testing environments. In contrast, people who had only the exocentric FOR had difficulty problem solving in the exo-referenced testing environment.
- Gender, simulator sickness, and usability were important predictors of mastery outcomes.
- Individual characteristics such as spatial ability and domain experience helped explain variability in the interaction experience.

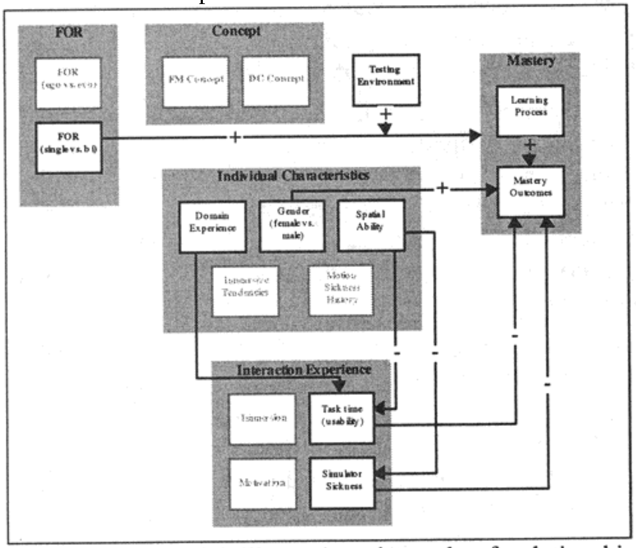

Figure 7. A model illustrating the web of relationships found in this study. Gray boxes represent factors that did not play a substantial role in this study.

CONCLUSIONS

Investigating the relationship between FORs and mastery in the context of other potentially important factors provided insights into both of our research questions.

How do FORs influence mastery? This study highlighted some important considerations when using FORs to support mastery of abstract information. First, people benefited from multiple FORs. Second, during the lessons, FORs seemed to highlight different information. However, at least in this study, these differences did not result in differential mastery of the concepts. Additionally, providing an egocentric FOR in a visualization tool seems to help people adopt that perspective when problem solving.

How do other factors influence the relationship between FORs and mastery? First, gender is an important issue to consider because it played a substantial role in influencing mastery. Second, at least in this study, the benefits of the FORs were not moderated by individual characteristics. Third, particularly important aspects of the interaction experience were usability (time on task) and simulator sickness because they influenced mastery. Finally, study outcomes suggested that we should consider both individual characteristics and interface characteristics (e.g., FORs) when trying to understand the interaction experience.

Recommendations for HCI research & design

This study's outcomes provide the basis for a number of recommendations for researchers and designers interested in understanding the strengths and weaknesses of FORs for visualization and mastery. HCI researchers, we recommend:

- Consider studying not only how single FORs affect performance but also how they work in combination. This study indicated that multiple FORs have: benefits.
- Carefully construct test environments to avoid bias yet provide ecological validity. The test environment can bias how FOR groups performed relative to one another. The strategy used in this study worked well: to create a mastery test that (1) assessed people's abilities to transfer what they learned to typical problems outside of the visualization environment and (2) provided a mechanism for checking the extent to which translating between FORs was an issue.
- Study the relationship between FORs and performance in a broader context. This study indicated that this relationship occurs within a complex. web of relationships among individual characteristics and facets of the interaction experience.
- Capture and analyze what people notice and. how they behave as they interact with FORs. In this study, the learning process was useful for assessing why mastery differed among the FORs.
- Address some of this study's limitations by investigating FORs in other visualization environments with different kinds of users and tasks.

We offer the following advice to designers of visualization environments.

- When the goal is to help people understand abstract information consider providing multiple FORs. In this study, the bicentric FOR facilitated mastery.

- When selecting one FOR over another, carefully consider the type of information the visualization environment needs to convey. The exocentric FOR can help draw user's attention to global aspects of the information; the egocentric FOR can be used to draw the user's attention to local information.
- It is important to think about the characteristics of the problem-solving environment to which users will be transferring their knowledge. For example, if the ability to adopt an egocentric perspective is important for learning or problem solving, enable users to do so in the visualization interface. This study showed that the people learning in the exocentric perspective had trouble adopting an egocentric perspective during problem solving.
- Consider how individual differences might affect how people respond to and learn from the visualization environment. Additionally, examine how visualization techniques affect interaction experiences and how those experiences impact task performance. In this study, gender, usability, and simulator sickness all had substantial impacts on mastery.
- Explore using FORs in combination with other visualization techniques. Assessing the potential of a variety of techniques can help us achieve McCormick, DeFanti, and Brown's vision for visualization tools [8].

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