

# USING VR'S FRAMES OF REFERENCE IN MASTERING ABSTRACT INFORMATION

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**Abstract:** This paper describes a research study that investigated the benefits of different immersive frames of reference (egocentric, exocentric, and a combination of the two) for mastering complex and multidimensional information. Based on study outcomes, we attempt to address several questions. First, how do FORs support mastery of abstract information? Second, does the nature of the problem solving environment matter? Third, how do individual characteristics and dimensions of the learning experience influence the relationship between FORs and mastery?

## 1. Introduction

The ability to work with abstract and multidimensional information is a crucial skill [West 1991]. Workers are required to navigate complex information to locate data, to identify patterns for problem solving, and to use sophisticated representations to communicate their ideas [Reiber 94]. In academic areas such as math, science, engineering, and statistics, students' success depends to a large extent upon their abilities to envision and manipulate abstract information [Gordin & Pea 95]. Finally, members of today's knowledge-based society must grapple with important political, environmental, and social issues that can be understood only through the integration and visualization of multidimensional data. Unfortunately, substantial research shows that visualization is difficult for most people [White 93; West 91]. Thus, techniques that can help people recognize patterns, reason qualitatively about physical processes, translate among frames of reference, and envision dynamic models are important.

Manipulating frames of reference (FORs), or different perspectives, is one of many techniques available to designers of visualization environments. Different FORs may be useful for highlighting different patterns and relationships in abstract information. Although there are numerous FORs, many can be classified as exocentric or egocentric. The *exocentric FOR* provides a view of an object, space, or phenomena from the outside looking in. The *egocentric FOR* provides a view of the object, space, or phenomena 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* allows users to alternate between the egocentric and exocentric FORs.

A review of research on FORs indicates they can influence what people attend to and what they learn [Presson, DeLange & Hazelrigg 89; Thorndike & Hayes-Roth 82]. This research provides the basis for the hypothesis that an egocentric FOR helps people make local judgments (concerning details in the information) and an exocentric FOR helps people make global judgments (concerning the "big picture"). However, this body of research focuses primarily on navigational tasks and provides little insight on using FORs to support mastery of abstract information.

Research in education and human-computer interaction also provides information relevant to the study of FORs as visualization tools [Halpern 92; Norman 95]. These studies underscore the importance of the roles that individual characteristics (e.g., gender, spatial ability, and domain experience) and learning experiences (e.g., usability, motivation, and presence) play in shaping the relationship between FORs and mastery.

## 2. Research Goals & Hypotheses

We designed this study to address the following research questions: (1) How can FORs support mastery of abstract information?; (2) Does the nature of the problem solving environment matter?; and (3) How do individual characteristics and dimensions of the learning experience influence the relationship between FORs and mastery? Based on our review of the literature, we had the following expectations:

- FORs would influence mastery. A combination of FORs would be better than a single FOR; there would be differences in what people learned from egocentric and exocentric FORs.
- People might have trouble transferring what they learned via one FOR to a problem solving environment that requires a different FOR.
- Individual characteristics and dimensions of the interaction experience would help to clarify the relationship between FORs and mastery.

### 3. Methods

The general design of this study was a mixed 3 (FOR group, between) x 2 (FM concept, within) x 2 (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. The DC concept and FM concept represent the kinds of information students worked with in the visualization environment: *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).

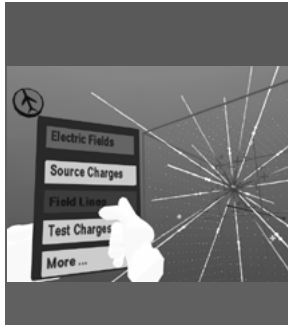
Forty-eight students, 30 males and 18 females, participated the study. They were juniors and seniors in advanced physics classes at a local high school. However, none of them were familiar with the electric field concepts covered in this study. Participants began the study by completing several questionnaires concerning their individual characteristics. Then, participants completed a lesson about electric fields using a visualization environment called MaxwellWorld (MW). They interacted with (MW) from one of three FORs: egocentric, exocentric, and bicentric. Learning process data was collected during this time. Immediately following the lesson, participants completed a series of questionnaires concerning their learning experiences. Approximately 3 days after completing the lessons, they participated in a testing session, during which their mastery of the concepts was assessed. At the very end of this session, students were asked to reflect on their participation via a follow-up interview. More information about the measures and materials is provided below.

#### 3.1 MaxwellWorld's Frames of Reference

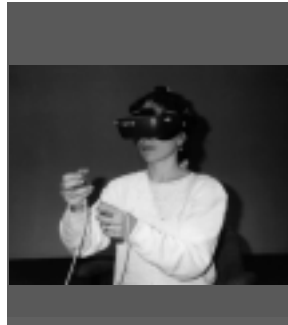
MW is an immersive VR visualization environment developed by Project ScienceSpace [Dede et al. in press]. MW is designed to help students master a complex and abstract domain of science - electric fields. In very simple terms, an electric field represents the distribution of force a standard charged particle (a test charge) would incur at any point throughout the space surrounding a charged particle. MW allows students to build electric fields by placing charged particles (source charges) in a 3-D space [Fig. 1]. Students can then manipulate abstract and multidimensional representations of the electric field. These representations (e.g., test charge traces, field lines, and moving test charges with path markers) provide information about the distribution of force in the electric field and show how a charged particle would move if it were released in the electric field.

MW's physical interface is typical of current high-end virtual reality. Hardware includes a Silicon Graphics Onyx Reality Engine2 graphics workstation, a Silicon Graphics Indy workstation, Virtual Research's VR4 headmounted display (HMD), a 3Ball, a menu device, and a Polhemus magnetic tracking system. The workstations are used to create the sounds and graphics used in MW. The remaining equipment enables a user to interact with MW. On his or her head, the user wears the HMD. In one hand, the user holds the 3Ball, which is represented in MW as a virtual hand. In the other hand, he or she holds a menu device, which is represented in MW as a hand holding a menu system [Fig. 2]. The Polhemus tracking system monitors the location of the HMD, the 3Ball, and the menu device. This enables the user to control where he or she is looking and to use the virtual hand, menus, and direct manipulation to perform tasks in MW.

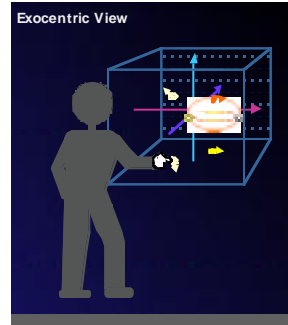
Students interacted with MW from one of three immersive FORs: egocentric, exocentric, and bicentric. In the exocentric FOR [Fig. 3], students explored electric fields as an observer from the edge of the fields. In the egocentric FOR [Fig. 4], students explored electric fields as a test charge immersed within the fields. In the bicentric FOR, students alternated between the egocentric and exocentric FORs for successive learning activities. Thus, bicentric students explored electric fields both as a test charge within the fields and as an observer from the edge of the fields.



**Figure 1:** Electric field and menu in MW.



**Figure 2:** A person interacting with MW.



**Figure 3:** Exocentric FOR in MW.



**Figure 4:** Egocentric FOR in MW.

### 3.2 Lessons & Concepts

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 several reasons. First, the principles underlying the phenomena are abstract and multidimensional. Second, mastery of electric fields requires students to perform typical visualization tasks: to work with abstract concepts, to imagine how changes to source charges change the field, and to recognize and understand patterns in electric field representations. Third, prior research with students studying electric fields demonstrated that they have trouble mastering electric field concepts [Dede et al. in press].

Students studied two aspects of the electric field (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): (1) *descriptive* (symbolic or “what” information such as definitions or representations) and (2) *causal* (conceptual or “why” information such as rules explaining relationships) [Shute 95]. To learn about force, students studied how forces were distributed in simple and complex electric fields, observed how changes to electric fields affected distributions of force, and tried to apply rules of superposition (the addition of forces). To learn about motion, students explored how test charges (imaginary charged particles) were propelled by forces in the electric fields. The concepts of force and motion were selected because an analysis of these concepts suggested that mastery of force would depend more heavily on global than local judgments and that mastery of motion would require more local than global judgments.

### 3.3 Learning Process & Mastery

Participants’ comments (predictions, observations, and synthesis statements) 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) included synthesis questions asking students to try to summarize key concepts.

The mastery test was a transfer test administered outside of MW. It was developed and refined based on the outcomes of several pilot tests and the expertise of two physicists who also teach this subject. To maximize the likelihood of detecting differences among the groups, the test was designed to push the edge of students’ knowledge. Tests consisted of several kinds of questions: conceptual questions, sketches, and demonstrations. Questions targeted both the FM concept (force and motion) and the DC concept (descriptive and causal).

Conceptual questions and sketches were administered via a paper and pencil test. Conceptual questions required students to imagine a force or motion scenario, determine whether it could be true, and explain why. Sketches required students to use the information presented in a sketch to answer questions about the distribution of force or the motion of a test charge within the field. Demonstrations were administered verbally using 3-D manipulatives and required students to explore electric fields and to demonstrate the distribution of force or the motion of a test charge within them.

### 3.4 Test Environment

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

### 3.5 Individual Characteristics & the Learning Experience

Individual characteristics included gender, domain experience (science and computer experience), spatial ability (spatial patterns and spatial visualization), immersive tendencies, and motion sickness history. ETS's CS-2 and VZ-2 [Ekerstrom et al. 94] were used to measure the two dimensions of spatial ability. Immersive Tendencies [Singer & Witmer 96] and Motion Sickness History [Kennedy et al. 93] questionnaires were used to assess each participant's propensity towards immersion and sickness.

To capture the learning experience, we measured immersion, simulator sickness, usability, and motivation. Presence [Singer & Witmer 96] and Simulator Sickness [Kennedy et al. 93] questionnaires 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.

### 3.6 Follow-up Interviews

At the very end of the study, students were asked to reflect on their experiences. They described what they liked and disliked about MW and identified the strengths and weaknesses of the FORs.

## 4. Results & Discussion

### 4.1 How do FORs support mastery of abstract information?

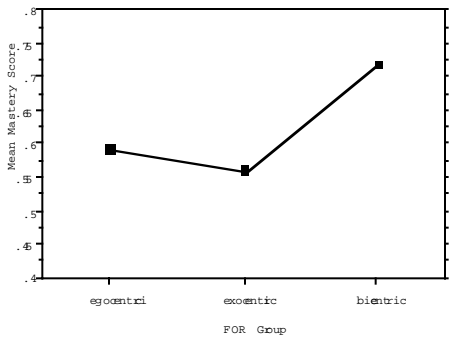
Learning process data, mastery outcomes, and interview outcomes indicate: (1) alternating between FORs during the lesson was more effective than using a single FOR; (2) the egocentric and exocentric FORs were useful in providing different kinds of information; and (3) the type of information highlighted by the egocentric and exocentric FORs did not lead to differential mastery of concepts selected for this study.

Mastery scores and learning process data show that the bicentric FOR facilitated mastery beyond the other FORs [Fig. 5]. An ANOVA on mastery scores (FOR group by FM concept by DC concept) reveals a significant main effect for FOR group ( $F_{\text{grp}}(2, 45) = 4.64, p = .01$ ). A planned comparison shows that the bicentric group had better mastery scores than either the egocentric group or exocentric groups ( $F_{\text{single-vs-bi}}(1, 45) = 9.20, p = .004$ ). Learning process data (accuracy and content of predictions, observations, and synthesis statements) further support this finding. Early on in the lessons, there was little difference in students' understanding. As the lessons progressed, the bicentric group outperformed the other groups. Figure 6 summarizes mean accuracy for the first and last synthesis questions (covering both force and motion). Note that mastery scores were highly and positively correlated with overall accuracy for synthesis questions ( $r(48) = .71, p = .0001$ ).

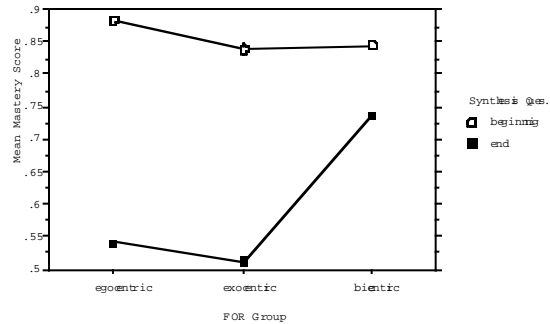
Learning process data and interviews suggest that the egocentric and exocentric FORs facilitated different kinds of observations. During the learning process, student observations sometimes depended on the FOR in which they were currently. For example, when asked to describe the electric field for a single source charge, 50% of the students in the exocentric FOR at the time (all of the exocentric group and half of the bicentric group) commented on its symmetry. Only 4% of the students in the egocentric group noted this. During the follow-up interviews, the students in the bicentric group were asked to comment on how they felt the egocentric and exocentric views supported their learning. All students felt that the FORs supported their learning in different ways. They found the egocentric FOR useful for providing details and felt that it helped them identify subtle changes in the motion of a test charge. However, they felt the egocentric FOR made them work at seeing the "big picture." The exocentric view provided a better overview of the information. When asked to reflect on the FORs, 91% of the students in the egocentric and exocentric groups

said that the alternative FOR would have been useful. Reasons were similar to those listed by the bicentric group.

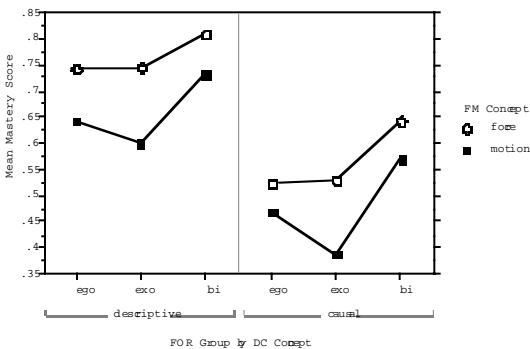
Despite evidence showing that the egocentric and exocentric FORs highlighted different kinds of information, we did not find that mastery of concepts (FM concept = force vs. motion; DC concept = descriptive vs. causal) differed as a function of the FORs in which students learned [Fig. 7]. An ANOVA (FOR group by FM concept by DC concept) on mastery scores reveals significant main effects for FM concept ( $F_{fm}(1, 45) = 32.33, p = .0001$ ) and DC concept ( $F_{dc}(1, 45) = 420.36, p = .0001$ ), but *no* significant interactions with FOR group. Of central interest to us here is the lack of interactions. In contrast to what we expected, the FORs did not differentially affect how well students mastered force and motion or descriptive (what) and causal (why) information. An examination of student answers suggests that students were using both global and local information across the concepts. Thus, it is likely that these concepts were not ideal for highlighting differences in the types of mastery afforded by the different FORs.



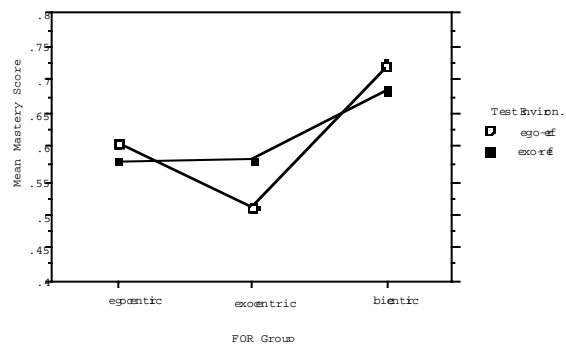
**Figure 5:** Mastery scores for each group.



**Figure 6:** Mean accuracy on synthesis questions. Not that questions at the end were much more difficult than questions at the beginning.



**Figure 7:** Mastery scores for each concept.



**Figure 8:** Mastery scores in different testing environments.

#### 4.2 Does the nature of the problem solving environment matter?

An ANOVA (FOR group by FM concept by test environment) on demonstration mastery scores indicates that 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) [Fig. 8]. There was not a main effect for test environment. Mastery (collapsed across FOR groups) on the ego-referenced portion of the test was roughly equivalent to mastery on exo-referenced portion of the test. However, there was a significant FOR group by test environment interaction ( $F_{grp*testenv}(2, 45) = 22.91, p = .0001$ ). Relative performance of the groups varied as a function of the test environment. Simple effects within each group (comparing ego- and exo-referenced performance) showed that exocentric group's ego-referenced scores were significantly lower ( $-0.070$ ) than their exo-referenced scores ( $F_{testenv@ego}(1, 15) = 9.53, p = .01$ ). The reverse was true of egocentric and bicentric groups ( $+0.028$  and  $+0.039$  respectively), although this difference was significant only for the bicentric group ( $F_{testenv@bi}(1, 15) = 5.96, p = .03$ ). To

summarize, the exocentric group had trouble adopting different FORs whereas the egocentric and exocentric groups did not.

### 4.3 How do individual characteristics and dimensions of the learning experience influence the relationship between FORs and mastery?

Both individual characteristics and learning experiences played important roles in shaping mastery. Individual characteristics explained 23.4% of the variability in mastery scores ( $R^2 = .234$ ,  $F(4, 44) = 3.28$ ,  $p = .02$ ). Of the individual characteristics, we had expected spatial ability to be the best predictor of mastery. However, gender was the best predictor. On average, males had higher scores than females ( $\beta_{\text{gender}} = .44$ ,  $t = 3.05$ ,  $p = .004$ ). Spatial ability (a linear composite of the CS-2 and VZ-2 test scores was used here) was marginally predictive of mastery ( $\beta_{\text{spat}} = .26$ ,  $t = 1.85$ ,  $p = .07$ ). We also found one aspect of domain experience (total science classes) to be predictive of mastery ( $\beta_{\text{sci}} = -.30$ ,  $t = -2.03$ ,  $p = .05$ ) while the other (hours per week using computers) was not. Somewhat counterintuitively, participants with more science classes tended to do more poorly on the mastery test. We also checked to see if the effects of FORs on mastery varied as a function of individual characteristics. We found they did not (there were no interactions between individual characteristics and FOR group). The benefit of the FORs for learning was consistent across different kinds of students.

Dimensions of the learning experience explained 30.1% of the variance in mastery scores ( $R^2 = .301$ ,  $F(6, 41) = 2.94$ ,  $p = .017$ ). The most predictive dimensions of the learning experience were task time and simulator sickness ( $\beta_{\text{time}} = -.369$ ,  $t = -2.645$ ,  $p = .012$ ;  $\beta_{\text{sick}} = -.333$ ,  $t = -2.174$ ,  $p = .036$ ). As expected, higher simulator sickness resulted in lower mastery; longer task times were also associated with poorer performance on the mastery test. Immersion, motivation, and other measures of usability were not significant predictors of mastery. There also was high variability in participants' learning experiences not explained by the FORs they used. Outcomes of a MANOVA suggest that the FOR group did not significantly predict usability, simulator sickness, immersion and motivation (Wilks  $\lambda = .742$ ,  $F(12, 80) = 1.17$ ,  $p = .32$ ). Instead, some aspects of the learning experience appear to have differed as a function of individual characteristics. For example, individual characteristics predicted approximately 30% of the variability in one aspect of usability - task time ( $R^2 = .300$ ,  $F(4, 43) = 4.60$ ,  $p = .004$ ). Participants with higher domain experience and spatial ability completed the lessons more efficiently. Spatial ability also was predictive of simulator sickness; students with higher spatial ability scores experienced fewer simulator sickness symptoms.

## 5. Conclusion

In this study, we tried to better understand FORs as visualization tools, whether the problem solving environment matters, and how individual characteristics and learning experiences affect mastery. We found:

- FORs do influence mastery. A combination of FORs has benefits for mastery. Thus, incorporating different FORs into visualization tools may help people work with and learn from abstract and multidimensional information. Additionally, study outcomes are consistent with the notion that the egocentric FOR supports local information while the exocentric FOR highlights global information. However, outcomes also demonstrate that this difference does not necessarily translate to noticeable differences in the mastery of concepts.
- People who haven't been exposed to the egocentric view may have trouble applying their knowledge in an egocentric problem solving environment. This is an important finding for designers of visualization environments because abstract thinking (particularly in the scientific domain) often requires the ability to adopt the egocentric perspective. There are numerous examples from everyday learning, research, and work when the ability to adopt an egocentric perspective is important. Consider a few: (1) a student struggling to understand what it would be like to be in a world without gravity and friction (something at which students are notoriously bad, [Halloun & Hestenes 85]); (2) a medical researcher trying to imagine processes inside a cell; and (3) an architect trying to envision what it would be like inside a building based on a tiny architectural model. In fact, educators often find themselves struggling to teach students to see things from the egocentric perspective [Pfister & Laws 95]. Thus, visualization tools that give people the ability to do this can be powerful.
- Individual characteristics can be helpful in explaining some of the variability in mastery. However, some of our findings are somewhat difficult to explain. In this study, gender was a powerful predictor. Spatial ability and domain experience also were relevant, but they did not explain gender differences in mastery as we had anticipated. Additionally, the finding that more science classes led to poorer performance was somewhat puzzling.

It may be that we weren't capturing the right aspects of spatial ability and that our domain experience measures (number of science classes, and computer usage) were too short-term to capture true domain experience. Thus, we are further investigating domain experience's role through follow-up interviews and examining other aspects of spatial ability in our other studies.

- Simulator sickness and task time were the most powerful predictors of the learning experience variables. The more positive the learning experience, the better the learning. In this study, these factors did not differ among the FOR groups. This is good news - it helps rule out the possibility that differences in the FOR groups' mastery were due to differences in the learning experience rather than to the FOR group. It also emphasizes the importance of designing visualization tools that provide a positive learning experience.

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