# Use of Reference Frame in Haptic Virtual Environments: Implications for Users with Visual Impairments

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**Abstract.** Reference frame is key in explaining the relationship between two objects. This paper focused on the orientation parameter of a reference frame in use of projective spatial terms, and its use by visually impaired participants using a haptic device to explore a haptic virtual environment. A total of nine visually impaired participants between 12 and 17 years of age participated in this study. After exploring the 3D virtual environment with a haptic device, participants answered questions about the frame they had utilized. Overall results indicated that the participants used relative frame of reference slightly more than the intrinsic frame of reference. This inclination was especially clear when both the target object and the reference object were on the horizontal plane. Only when objects were on horizontal plane but intrinsically vertical to the reference object, the intrinsic frame of reference was preferred. We also found evidence that participants used a reflective subtype of the relative frame, and vertically aligned objects were easy to be perceived with the relative reference frame. We concluded that the virtual environment and haptic input had influence on the result by separating the user from the computer, only allowing one point of contact. Thus it would be possible to apply the result of this study to the development and assessment of assistive technology for people with visual impairment, especially in regard to how spatial information between the systems and the user is communicated.

**Keywords:** Reference frame, relative frame, intrinsic frame, projective spatial terms, visual impairments.

## 1 Introduction

When people explain a spatial relationship between two objects, especially the direction from one to the other, they use projective spatial terms such as ‘left’, ‘front’, ‘above’, and so on. Use of such terms is based on different frames of reference. Imagine you are facing a computer screen, with a coffee cup placed on the right hand side of the screen. The coffee cup is obviously ‘to the right of the screen’, but at the same time, it is ‘to the left of the screen’ from the perspective of the screen. The difference between these two explanations comes from different frames of reference that each sentence buys. The first sentence implies ‘relative’ frame of reference, and the second sentence implies ‘intrinsic’ frame of reference.

M. Kurosu (Ed.): Human-Computer Interaction, Part IV, HCII 2013, LNCS 8007, pp. 610–617, 2013.

There is a wealth of distinctions across many disciplines that explicitly use the term ‘spatial frames of reference’. In this paper, we used the three linguistic frames of reference defined by Levinson [1].

- Intrinsic frame of reference: The coordinate system that uses features of the reference object to explain the location of the target object.
- Relative frame of reference: The coordinate system that is established by the position and functional-spatial structure of an additional entity, usually an egocentric viewpoint.
- Absolute frame of reference: The coordinate system that uses features of the environment, such as gravity, cardinal directions, or landmarks.

Appropriate implementation of a reference frame is associated with the viewpoint people take when they create a spatial mental map. It is especially important for visually impaired people because spatial language acts as an alternative to visual information. Many papers indicate that vision is not the only modality utilized in creating mental maps; the nature of spatial images is supramodal [2] [3] [4]. In many studies, people were able to convert verbal descriptions into mental representations that are similar to and function equivalently with the mental representation derived from visual experience [5] [6] [7].

One point to consider is that the cognitive processes of people with visual impairment may differ from that of sighted people. Levinson [1] suggested that there might be differences between visually impaired people and normally sighted people in spatial language, largely due to the dependency of language-space interaction on former experience, rather than given priory. A review by Cattaneo et al. [8] reported that cognitive mechanisms, or mental processes, are strongly affected by the nature of perceptual input on which people commonly rely on.

In particular, there is evidence that people with visual impairment prefer the intrinsic frame of reference. Struiksma and colleagues [9] conducted an experiment using projective spatial terms in order to observe the preference of reference frame among blind people, low-vision people, and sighted people groups. The results indicated that the blind group showed a clear preference for the intrinsic frame, when judging spatial relation in the horizontal plane. According to the study of Postma et al. [10], sighted people tended to prefer the absolute reference frame in order to point out the locations of objects, while blind people would rather use the intrinsic reference frame.

Nevertheless, there is no previous research on reference frames in haptically enhanced virtual environments, despite the fact that haptic virtual environments can enhance learning of people with visual impairment as an assistive technology. Lahav and Mioduser [11] tested a virtual environment with a haptic device in order to provide visually impaired people with prior spatial information on unexplored space. In such a situation, we assume that feedback with accurate spatial language will enhance the usability and reliability of a system.

This paper focused on exploration of a haptically enhanced virtual environment and investigated which reference frame people with visual impairment prefer in order to perceive the spatial relationship between two objects. The results of the present study may serve as a basis for the study of spatial language in haptic virtual environments. In addition, it will suggest ways to minimize system-to-user or user-to-user communication. In the following sections, we will introduce our system and experiment procedure, and discuss the results we obtained.

# 2 Methods

## 2.1 Participants

We recruited participants from a local school for the blind. Nine participants were included with varying degrees of blindness; three participants were totally blind, one was nearly totally blind, and five were partially blind. The ages of participants were between 12 and 17, and in middle or high school (between 6th and 11th grade). Three participants were male, and six participants were female.

## 2.2 System

New software was developed based on Novint Falcon SDK to create the 3D experimental virtual environment. The system enabled arrangement of objects of desired shapes and sizes in a 3D space. When stimuli were arranged in the 3D space, users could detect them with a Novint Falcon haptically enhanced 3D touch controller.

## 2.3 Stimuli

Two stimuli were utilized: a target object and a reference object. The target object was a ball (represented as a sphere), and the reference object was a car (represented as a cube). These objects were placed in the virtual 3D space, where no wall, floor, or ceiling is detected. To create a orientation cue for the reference object, we provided a miniature of the car (10cm×5cm×3cm) fixed on a wooden plate in the real world, whose configuration was altered based on a layout of each trial. Experimenters verified that participants understood the directionality of the toy car (i.e., which side is front, left, and above) before the experiment.

During the experiment, the participants detected overall layout of stimuli in the virtual world by controlling the Falcon device with their dominant hand. At the same time, they could feel the shape and direction of the reference object (miniature car).

## 2.4 Procedure

Throughout the experiment, participants were seated on a chair in front of a computer desk. The Falcon device was located on the desk, on the side of each participant's dominant hand. The wooden plate holding the miniature of the reference object was placed in front of the participants. The computer screen was turned to the experimenter and away from the subject to prevent partially blind participants from seeing the screen.

We used the terms 'front', 'left', and 'above' to represent three axes of the 3D space, and two different frames of reference: intrinsic and relative/absolute. The absolute frame of reference goes together with the relative frame of reference in this case because gravity determines the vertical axis of body posture, a basis of the relative frame of reference.

Each cell in the Table 1 below indicates each trial. For example, the trial in the second column of the first row, layout 2, represents the relationship between objects that can be either "the ball is on the left of the car" (based on relative/absolute frame) or "the ball is in front of the car" (based on intrinsic frame). We removed three cells that use same terms for both reference frames (grey cells) because of redundancy.

**Table 1.** Layout

| | | | ***Relative*** | |
|---|---|---|---|---|
| | | **Front** | **Left** | **Above** |
| | **Front** | Layout 1 | Layout 2 | Layout 3 |
| ***Intrinsic*** | **Left** | Layout 4 | Layout 5 | Layout 6 |
| | **Above** | Layout 7 | Layout 8 | Layout 9 |

For each layout, the participants were given enough time to explore the layout of the virtual environment with the haptic device. Then, they were asked to judge the truth or falsehood of two statements describing the relationship between objects. For instance, in the example mentioned above, participants were to give answers to both "the ball is on the left of the car" (true based on relative/absolute frame) and "the ball is in front of the car" (true based on intrinsic frame).

## 3 Result and Discussion

Each participant judged truth and falsehood of two statements describing each of six layouts. Hence, we could have 108 boolean data points in total. If one used relative reference frame, he or she would have answered true to the relative frame based projective spatial term (e.g., in layout 2, a participant would say 'true' to the term 'left' if relative frame is used, but say 'false' to the term 'in front'). If they used intrinsic reference frame, they would have answered true to the intrinsic frame based term (e.g., in layout 2, a participant would say 'true' to the term 'in front' if intrinsic frame is used, but say 'false' to the term 'left')

On average, 55.56% among all responses were answered true to the relative frame, whereas 46.30% answered true to the intrinsic frame. The sum of these two is not equal to 100% because only 64.81% used one reference frame at a time. Among those who used single frame at a time, 57.14% used the relative frame and 42.86% used the intrinsic frame. Figure 1 shows this tendency with the proportion of participants saying 'true' to both frames (18.52%), and 'false' to both frames (16.67%).

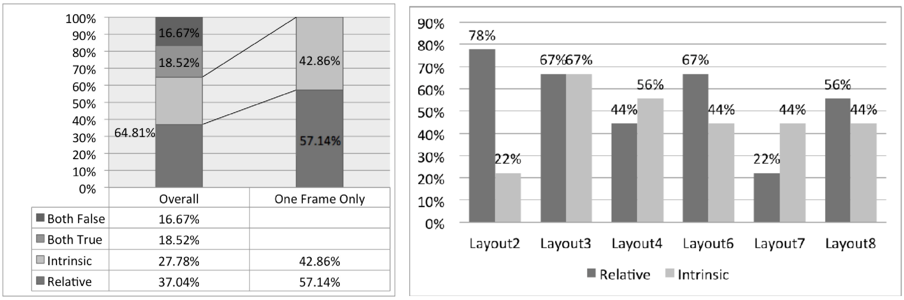


**Fig. 1.** Overall results *(left)* and result from each layout *(right)*

The graph on the right side of the Figure 1 shows the results from each layout. Among six layouts, the participants tended to use relative reference frame in the case of layout 2, 6, and 8, while they tended to use intrinsic frame in layout 4 and 7.

To analyze the results for each frame, we first combined the results focusing on relative reference frame. For instance, if we combine layouts 4 and 7, it is the case when 'front' indicates relative reference frame, regardless of the intrinsic reference frame. In the same sense, we integrated layouts 2 and 8, and layouts 3 and 6. As a result, it turned out that participants tended to use intrinsic frame in the first combination where 'front' indicates relative reference frame. Other trials where 'left' and 'above' indicates relative reference frame, however, the participants tended to use the relative frame rather than the intrinsic frame.

If we instead disregard relative frame, layouts 2 and 3 can tied together where 'front' represents intrinsic frame. Similarly, layouts 4 and 6, and layouts 7 and 8 fell into the same category. In this case, participants tended to use the intrinsic frame when 'above' represents intrinsic frame (the combination of layout 7 and 8). Yet, we could not find clear preference to the intrinsic frame, as the difference was too small.

Figure 2 demonstrates the results described above. This analysis also suggests that the relative frame was dominant in general. The graph with error bars shows that there was no case when the intrinsic frame outperformed the relative frame. (The ambiguous 'front' case in the left graph is discussed in Figure 3.)

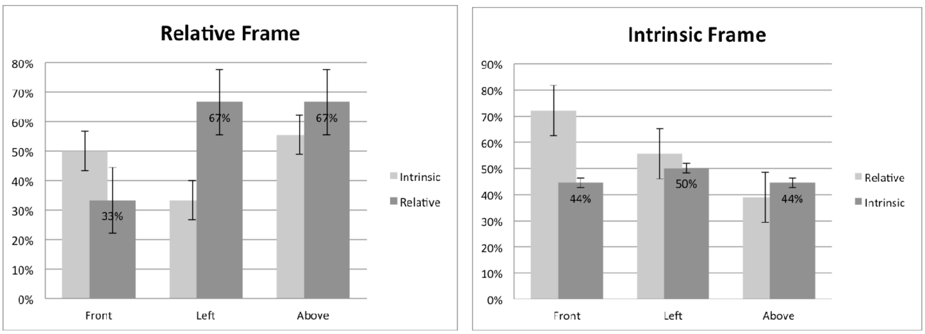


**Fig. 2.** Percentage of selecting each reference frame for a specific term

We also investigated the results in terms of spatial planes: horizontal and vertical. We combined layout 2 and layout 4 together, as both layouts are explainable with horizontal terms, either 'front' or 'left', regardless of the frame (HH). Likewise, we integrated layout 3 and layout 6. In both cases, relative frame corresponds to the vertical term 'above', and intrinsic frame corresponds to the horizontal term 'left' or 'front' (VH). Layout 7 and layout 8 used the term 'left' or 'front' for relative frame and 'above' for intrinsic frame (HV). The graph on the left side of Figure 3 outlines the result of this integration. The participants showed preference to the relative frame when the two objects were on the horizontal plane, which is a canonical situation. The tendency was similar when the target object was relatively above, even though it is a non-canonical situation. However, this trend was marginally inversed when the objects were on the horizontal plane but the target object was intrinsically above the reference object. It suggests that the proportion of people who think in the perspective of the reference object increases when it is a non-canonical situation and the objects are not aligned on the vertical plane.

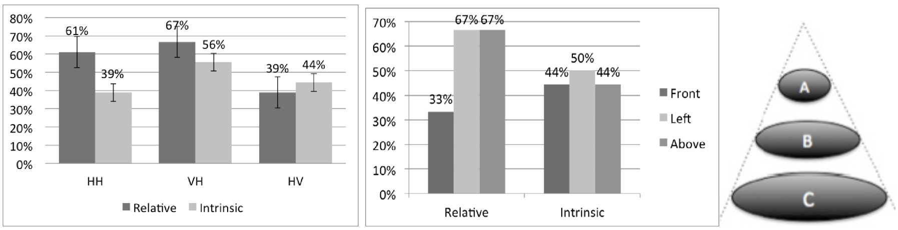


**Fig. 3.** Percentage for choosing either reference frame, under three types of layout: two objects are on the horizontal plane and intrinsically horizontal (HH), two objects are on the vertical planes but intrinsically horizontal (VH), and two objects are on the horizontal plane but intrinsically vertical (HV) *(left)*; Percentage of 'true' answers for each reference frame under a specific term *(middle)*; the 'front' concept *(right)*

The case where participants answered 'both false' or 'both true' led to an interesting result. Out of five participants who answered false to both frames, four made 'both false' answer to the layout 7, where the target object was relatively front but intrinsically above. One possible explanation is that the participants thought the target object was relatively 'behind' the reference object. The graph in the middle of Figure 3 shows the percentage of 'true' to each frame, which is part of Figure 2. We can find a noticeable outlier on the far left side; the ratio of 'true' answer to the 'front' was significantly lower than other cases of the relative frame. One possible explanation is that the participants did not perceive our intended 'front' as 'front'. In the experiment, we assumed that the target object is in front of the reference object when it is further away. The diagram on the right side of Figure 3 explains this; what we intended was that 'A is in front of B'. However, the result suggests that participants might have perceived 'C is in the front of B'.

Such difference yields subtypes of the relative reference frame: translation and reflection. When a target object beyond a reference object is considered to be 'in front of' the reference object, it is of the translation subtype; when a target object between a perceiver is considered to be ‘in front of’ the reference object, it is of the reflection subtype. Generally, different language affects customs of such subtypes, and English entails the reflection subtype (Cox 1981, Levinson 2003, Bender et al. 2005). The inclination of English speakers to rotate their body orientation by 180 degrees when they use the relative frame of reference may have caused the interesting outcome.

Furthermore, out of ten cases where the participants answered ‘true’, six cases were from layout 3 and 6, or VH case (vertical term stands for relative frame, and horizontal terms stand for intrinsic frame). It implies that absolute above is easy to perceive and stable regardless of the intrinsic orientation of a reference object. It partially coincides with previous research from Struiksma et al. [9], where the blind people showed relatively low bias to the intrinsic frame of reference when the objects were aligned vertically.

Our study results showed more familiarity with the relative frame of reference in general, which does not match with the previous experiments where relatively large number of intrinsic reference frame responses took place. First, it may be due to the virtual environment providing fewer sensory cues than most physical environments, causing lower presence in the virtual environment [12]. Since the virtual environment lacks sensory channels, it could be hard for the users to think in the perspective of the reference object, or intrinsic frame. If this is a correct explanation, we can also suggest the reference frame test as a tool to assess the level of engagement in the virtual reality, breaking boundaries of traditional subjective questionnaire methods [13].

Second, the ambiguity caused by one-point movement might have influenced the perception. The haptic inspection of configurations required one point exploration in this study; with Novint Falcon, the participant could only touch the virtual objects with a one-point cursor, on the contrary to the ordinary haptic situations where they normally employ two hands and ten fingers. Subjective inspection also showed that the surface area of objects they actually touched was relatively small. It is possible that the limited touch caused confusion and resulted in participants using the relative frame of reference, which is fairly easy to apply in that it does not require any mental rotation.

# 4 Conclusion

The participants with visual impairments used the relative reference frame in preference to the intrinsic reference frame when they perceived the objects in a 3D virtual environment. This tendency was constant, except for the case where the target object is intrinsically above in relation to the reference object. The results dissent from the studies prior to this research, where people with visual impairment mostly preferred the intrinsic frame of reference. As the former studies were conducted in the real world using real objects, the virtual environment might have produced different aspects of perception, in terms of framing spatial relationships. The characteristic of haptic exploration could be one other factor that caused people to use the relative frame as well.

To improve the precision of results, a larger sample size with more encompassing statistical analysis is required. Furthermore, we cannot ignore cultural effects.

Considering the participant groups with different cultural backgrounds in different papers, we will be able to make stronger suggestions if we compare the results to those of a group of sighted people within a same culture and age group.

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