Measuring an Illusion: The Influence of System Performance on Size Perception in Virtual Environments

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Abstract: The effects of system performance variations on people's estimation of virtual object sizes in a multi-sided back projection virtual reality system have been explored. Seventy-seven participants adjusted the sizes of three subsequently displayed simple virtual shapes to the memorized sizes of corresponding real objects. The sizes of the virtual objects have been calibrated in real space. With low system lag (i.e., high system performance), object sizes were underestimated. With high system lag participants perceived the virtual objects significantly larger than while experiencing the high performance condition. An explanation for this effect relying on a proposed cognitive averaging process of motion-dependent size cues has been suggested. In addition, an increase in estimation variance among participants has been detected when the system lag was increased. A control experiment (real-to-real objects size comparisons) proved good applicability of the estimation method used.

Keywords: virtual environments, size perception, system performance

1 Introduction

For effective use of many existing and future applications of virtual environments (VEs), thorough knowledge about the factors influencing size and distance perception in VEs is crucial. Classic examples are applications that shall enable transfer of training and spatial knowledge from the VE to the real world (or vice versa). Others include VEs for assessing spatial properties of real world objects via analysing their virtual substitutes. The latter application is especially important in product development processes of divers industries, ranging from hand held information technology development to automobile and all the way to factory design.

1.1 Factors affecting spatial perception in VEs

Factors affecting size and distance perception in real environments have been subject to intense research for decades; see e.g. Gillam (1995) and Cutting and Vishton (1995) for reviews. Only in recent years, a number of studies has been published on factors affecting spatial perception in VEs. Various system related and cognitive factors have been analysed, including the variation of display type (e.g. Henry & Furness, 1993; Ellis & Menges, 1997; Bullinger et al., 1998; Waller, 1999), texture and stimulus size as well as navigational interface (Witmer & Kline, 1998), scene contrast (Eggleston et al., 1996), field of view (Waller, 1999; and references therein), error-corrective feedback (Waller, 1999), and distance cue type (Surdick, 1997). The majority of these studies were concerned with egocentric distance estimations, egocentric meaning that one end point of the judged distance is the observer.

1.2 Overestimation vs. underestimation

Plenty of research work has been conducted to determine the direction (overestimation or underestimation) and degree of estimation errors of distance and size judgements in real environments. Results are diverse, but as a general rule egocentric distances seem to be underestimated in many cases, whereas exocentric distances (those between objects) often tend to be overestimated (see Waller, 1999, for a concise review). This general behaviour has been observed in VEs as well. For instance, Witmer and Kline (1998) as well as Henry and Furness (1993) found strong underestimation of egocentric and mixed egocentric and exocentric distances, respectively; Waller's (1999) experiments exhibited an average overestimation in exocentric distance judgements.

1.3 Staying with us: system lag

In addition to the variation of the parameters mentioned in section 1.1, it has been suggested (Witmer & Kline, 1998) but to our knowledge not yet been shown that system performance, or system lag, has an effect on spatial perception in VEs (throughout this article, the term *system lag* is used to denote the time delay between a user motion and the corresponding adjustment of the display contents, thus including the phase lag of the tracking system, delays due to high rendering times/low frame rates, and possible other effects). Today, significant system lags are still not restricted to low-end virtual reality systems. Particularly VEs for product development and styling processes are often considered to require high degrees of pictorial realism and three-dimensional detail, thus producing a strongly perceivable system lag even using today's high end graphics engines. There is no way to rule out that the co-evolution of system power and user demands concerning handled data volumes is going to persist in the near future, underlining the importance of studying system performance-related effects.

1.4 The objective of this study

In the light of the points mentioned in sections 1.1, 1.2, and 1.3, the objective of the present paper was to investigate the effects of system lag (as induced by varied rendering frame rates) on the users' perception of exocentric distances, in this case object sizes. We did so by having participants compare the sizes of virtual objects to those of real objects seen beforehand as a mental reference. No direct perceptual frame of reference (familiar objects, grid etc.) was given in the VE.

This procedure enabled us not only to analyse effects on size estimation due to variations of system lag in the VE, but also to simultaneously compare participants' estimations to their real world size perception. The comparability to real world perception is essential for many practical applications. To ensure this comparability and to exclude a possible scaling bias caused by the tracking or projection system, we calibrated the dimensions of the virtual objects in real space.

2 Method

2.1 Participants, apparatus, and stimuli

Seventy-seven people participated in the study (9 women and 68 men). The virtual objects assessed were positioned near the middle of a cubic-shaped five-sided back projection system (2.5 m length of side). The objects were thus comfortably viewable in side-elevation while standing. The virtual environment ran on an Silicon Graphics® Onyx2 • graphics engine. The participants' head movements were tracked with a six-DOF tracker (MotionStar® by Ascension®), the left and right eye channels were separated using StereoGraphics® CrystalEyes® shutter glasses. The system lag was controlled by selectively adding a highly complex (invisible) object, slowing down the frame rate to appr. 3 frames/s (for each eye). For the high performance situation this object was removed (frame rate appr. 57 frames/s for each eye).

The three virtual objects to be assessed were a stick, a sheet, and a box (basic dimensions of (a) stick: 50 by 0.5 cm, (b) sheet: 50 by 30 by 0.5 cm, (c) box: 50 by 30 by 40 cm). No other virtual objects were displayed within the participants' field of vision in order to prevent size estimations through direct comparison. The sizes of the virtual objects could be increased or decreased by scaling factors of ($n \times 1.04$) or ($n \times 0.96$), respectively, along all three axes uniformly ($n = 1, 2, 3...$). In addition, a series of differently sized real objects of each type was provided, featuring the same scaling steps as the virtual objects.

2.2 Procedure

The participants' task was to memorize the size of a particular real object and to subsequently choose the corresponding virtual object with the size fitting their memory of the real object best. The first size displayed was slightly off the correct size. The participant had to decide whether the currently displayed object was too big, too small or correct in size compared to the real object seen just shortly beforehand. The participant gave her or his assessment aloud, and the operator immediately adjusted the size of the object by one step (of 4 % along each cartesian axis) in the indicated direction. This procedure was repeated until the participant judged the size to be correct. This size was recorded (*real-to-virtual comparison*). Having left the projection room, participants were shown a single real object again. Out of five differently sized corresponding real objects, they then chose the one that fitted the memorized size of the single object best (*real-to-real comparison*). Here, participants in both system lag groups experienced the same stimuli (control experiment).

Each participant assessed all three types of objects (stick, sheet, and box) in the two combinations real-to-virtual and real-to-real. The real-to-real comparison was included to check on the participants' performance in a corresponding task without virtual stimuli. The objects' order of presentation was randomized to prevent transfer effects. The participants were randomly assigned to the low and high system lag situations (n_{low} = 42, n_{high} = 35). Each of them experienced only one of the settings, again in order to prevent transfer effects. Prior to each experiment each participant's interocular distance was measured, enabling the software to correct for these differences by adapting the projected images.

2.3 Calibration

The aim of the calibration process was to determine the sizes of the projected virtual objects in real space. For this purpose we measured the x-, y-, and z-dimensions of the projected objects using a transparent, real ruler (n = 10 for each object and dimension, estimated reading error 0,5 cm, standard deviation 0.4-0.9 cm). For the sheet and the box, the calibration values for x- and y-directions or x-, y-, and z-directions, respectively, have been averaged as participants were able and encouraged to view the objects from different directions.

3 Results

3.1 Mean Size Estimation

The participants' size estimations were averaged separately within the twelve settings (three object types in real-to-virtual and real-to-real combinations in two system lag settings). Figures 1 (a-c) show the mean size estimation errors for each setting. The size estimation error is defined as the ratio of the size of the chosen virtual (real) object and that of the corresponding real object the size of which was to be matched. Thus, a positive estimation error indicates an *underestimation* of the size of the chosen virtual (real) object. Note that the estimation error describes uniform differences along all three Cartesian axes for all three objects. The zero lines in Figures 1 (a-c) were calibrated as described in (2.3). For each object type and within each combination, the mean values for the low and high system lag settings were subject to separate variance analyses. In the real-to-real combination, low and high system lag groups experienced the same conditions (control experiment).

Variance analysis: real-to-virtual. In the real-to-virtual combination, the variance analyses yielded significant differences between low and high system lag settings at the 0.10 level for the sheet ($F(1, 75) = 2.81$, $p = 0.098$) and the box ($F(1, 75) = 3.99$, $p = 0.050$). In both cases the participants chose bigger objects in the low system lag situation, the differences of the mean estimation errors ($error_{low} - error_{high}$) being 2.76 % (sheet) and 3.89 % (box). For the stick, the variance analysis yielded a not significant result ($F(1, 75) = 2.09$, $p = 0.153$). Though not being significant, one could argue that the tendency observed in the other two cases stays the same (bigger objects being chosen in the low system lag setting). As can be seen in Figures 1 (a-c), the mean estimation errors have relatively high positive values in the same order of magnitude for all three object types in the low system lag situation (2.91, 2.99, and

2.33 % for stick, sheet, and box, respectively). For the high system lag situation, the mean estimation errors are comparatively small (-0.37, 0.23, and -1.56 %, respectively).

Variance analysis: real-to-real. No significant differences were found across high and low system lag subject groups, as expected due to the identical conditions in this part of the experiment (stick: $F(1, 75) = 0.06$, $p = 0.807$; sheet: $F(1, 75) = 2.00$, $p = 0.161$; box: $F(1, 75) = 0.68$, $p = 0.413$).

3.2 Estimation Variance Comparison

Additionally, we compared the estimation variance within the settings across system lag situations for the real-to-virtual combination (Figure 1d). The comparison yielded significant dependencies of the estimation variance on system lag for all three object types at the 0.10 level (as well as 0.05 and 0.01 levels for box and sheet, respectively): Experimental F-values were $F_{stick} = 1.60$, $F_{sheet} = 2.55$, $F_{box} = 1.76$ (see Bortz, 1989, for F-value extraction), the corresponding theoretical F-values are $F_{90\%}(34, 41)$

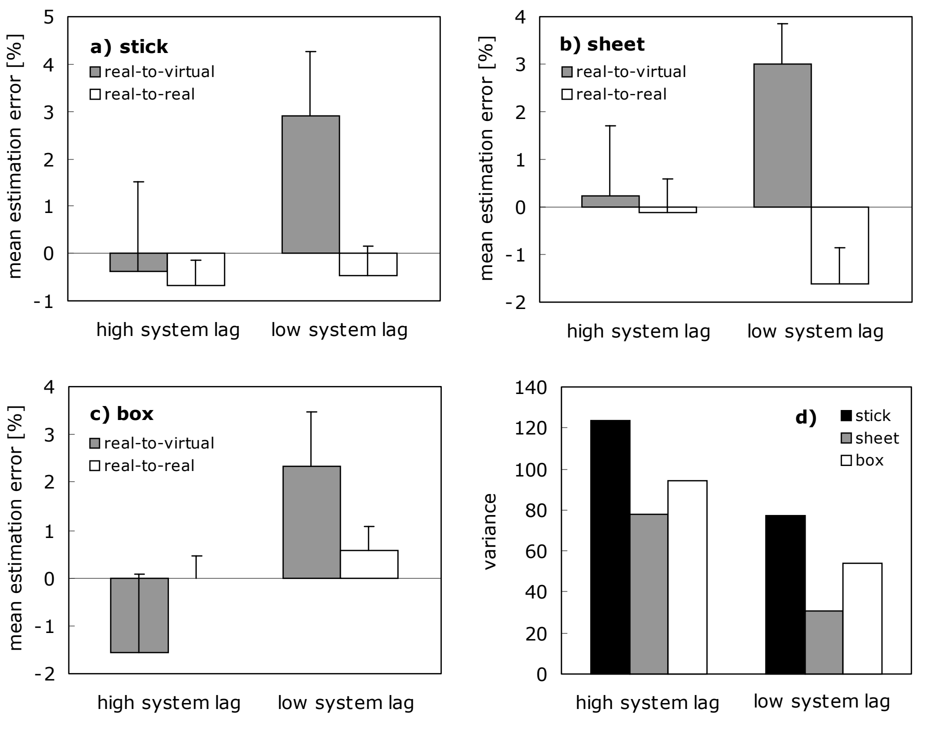

Fig. 1. (a-c) Mean size estimation errors (and standard errors of the mean) for stick, sheet, and box in real-to-virtual and real-to-real comparisons and for high and low system lags (in the real-to-real control experiment, high and low system lag groups experienced the same stimuli). Positive estimation errors denote underestimation; see the text for a definition of the size estimation error. The percentages given describe uniform scaling along all three cartesian axes. (d) Estimation variance for stick, sheet, and box in the real-to-virtual setting for high and low system lag.

= 1.54, $F_{95\%}(34, 41) = 1.74$, $F_{99\%}(34, 41) = 2.20$. In all cases the variance was smaller in the low system lag situation.

4 Discussion

Three main outcomings are to be discussed: (1) For all three geometric shapes, the high system lag situation generated a mean estimation error (as defined above) smaller in magnitude than the low system lag situation. In fact the estimation errors were well below 0.5 % for stick and sheet with high system lag. (2) Equal in direction and similar in magnitude for all three object types, a decrease of the system lag let participants perceive the virtual objects *smaller* (statistically significant for sheet and box). (3) Comparison of the estimation variance exhibited a lower variance for the low system lag (significant in all three cases).

4.1 Result one

At first glance, result (1) seems to suggest that it is the *high* system lag (which in this experiment is very high indeed) that allows *more accurate* estimations. This appears to be counterintuitive, as the high system lag situation is for sure the less 'natural' one and therefore prone to disturb normal size perception processes. The following section helps resolving this contradiction.

4.2 Result two

Why has the variation of the system lag – as described in result (2) – influenced participants' size perception? We suggest the following possible explanation.

The effect observed has to be linked directly with the participants' motion relative to the objects. If not moving, participants in the high and low system lag situations experienced exactly the same stimuli (the objects were fixed in space). The participants' motion was predominantly sideways with a slight rotation of their heads as they watched the objects from varying angles. Alternatively, they just turned their heads, looking back and forth from one side of the object to the other. To a first approximation, the turning of the head results in a movement very similar to a small sideways movement, since (1) they only slightly turned their heads to achieve this and (2) the natural axis of horizontal head rotation runs through the back of one's head. Figures 2 (d) illustrates this schematically.

Figure 2 (a) shows the geometric situation for an observer viewing a virtual object A without moving. The observer perceives it stereoscopically floating in front of her or him by looking at images B and C that are projected on screen D. Image B can only be viewed with the right eye, C only with the left. If the observer moves to the right, keeping the eyes on the same line, and only looks at the images again when the system has had enough time to adapt the display contents to the new tracker position, then the geometric situation is as shown in Figure 2 (c). Object A virtually stays in place, images A and B have been shifted (to A' and B', respectively). In an ideal system (zero lag), this adjustment is correct also *during* movements. As the objects in this experiment are very simple, our low system lag situation is close to an ideal system in this respect.

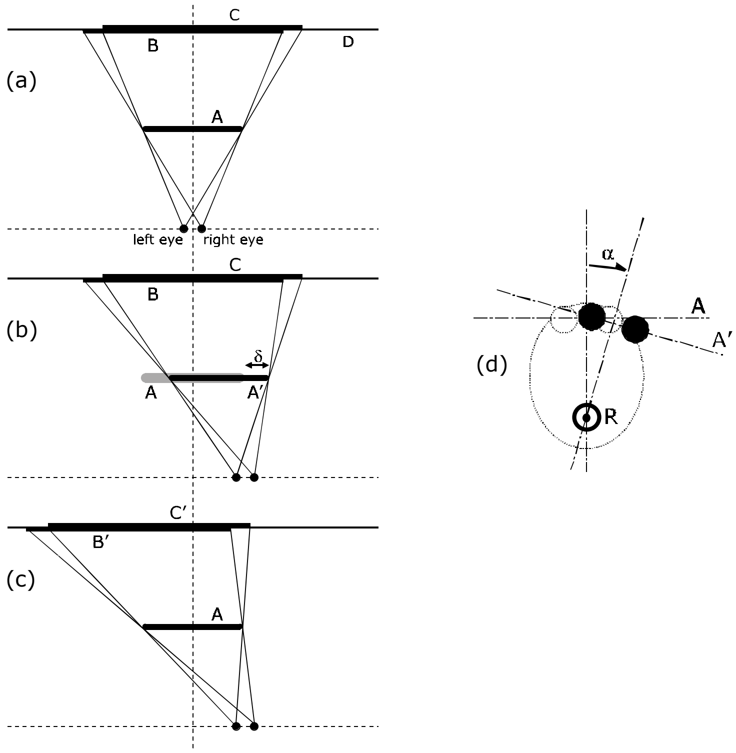

Fig. 2. (a-c) Schematic representations of a person perceiving a virtual object A by viewing a double picture B/C (B'/C') on a projection screen D. (a) Static viewing conditions; (b) intermediate viewing conditions with strong system lag, the observer has shifted to the right, but pictures B/C have not been adapted yet, resulting in a perceived shift of virtual object A by a distance δ to position A'; (c) adapted viewing conditions instantly achieved after a move to the right in an ideal system, but with a strong system lag only after a perceivable period of time. (d) Schematic overhead view of a person slightly turning her or his head. To a first approximation, a 'natural' head rotation by a small angle α (R = axis of rotation) results in a similar geometric situation as a slight shift of the head to the side.

The situation is different for a high system lag: if the observer quickly moves to the right, the system is too slow to adjust images B and C instantaneously. Figure 2 (b) shows the resulting geometric situation for the extreme case that images B and C are still in the same position as in Figure 2 (a), whereas the observer has finished her or his movement already. Thus, the observer perceives the virtual object *shifted to the right* (A'). If the observer stays in this position, the virtual objects then gradually moves back to its original position (A) as the graphics engine adjusts images B and C (resulting in B' and C'; see Figure 2 (c)). Similar effects are, of course, observed with similar movements in other directions.

This shifting of the virtual object alone does not account for the difference in size estimations as a function of system lag, as the length of A' equals that of A (intercept theorems) and their perceived distance is nearly the same (no significant change in distance cues). But taking into account that one is usually directing one's line of sight in the direction of the movement and/or rotation (looking at the right side of the virtual object while turning the head to the right), the following explanation seems plausible: With the majority of sideways movements or head rotations, the observer apparently views an object *temporarily enlarged on one side* – the side just looked at primarily (see Figure 5 for an illustration). The fact that the object is shortened by the same amount on the other side (the one not in the line of sight) seems to be neglected by the observer in comparison. Because participants were able and encouraged to view the objects from different directions, they moved a lot, thus being exposed to constantly changing size cues. The most straightforward cognitive strategy for resolving the changing size cue conflict we can think of is an averaging process. Consequently, participants might have had an overall impression of a slightly enlarged object; the degree of enlargement did then depend on their movement rate.

In the low system lag situation such an effect cannot occur. Hence, coming back to the discussion of result (1), participants' size estimations were more accurate experiencing a low system lag, as common sense had already suggested.

4.3 Result three

On the basis of the proposed explanation for result (2), a straightforward explanation for result (3) is possible as well. Given that the participants were free to choose the amount of their movement, there is good reason to believe that the amount of movement is distributed statistically across participants. If the size estimations are dependent on the overall amount of movement in the high system lag setting, the estimations should exhibit an increasing variance with increasing the system lag. This is exactly what we found in our experiments. It should be noted though that more participants were (randomly) assigned to the low system lag setting than to the high system lag situation ($n_{low} = 42$, $n_{high} = 35$), possibly enhancing the observed effect.

4.4 Why underestimation?

In the optimum estimation condition (low system lag), the sizes of the virtual objects are generally underestimated in our experiment. We currently have no explanation for this observation. A review of the literature (see section 1.2) shows divers results of similar experiments, exhibiting both overestimation and underestimation. It has to be added that the calibration process described in section 2.3 is arbitrary to some extent. A separate calibration for x, y, and z yields different zero lines in Figures 1 (a-c). Possibly, participants have given unequal weights along the different spatial axes in their estimations, either statistically varying interpersonally or even varying systematically. With the described experiment we could not account for that.

4.5 The effect of 'adding dimensions'

The F-values for the mean estimation error differences between high and low system lag settings are increasing from stick to sheet to box, reaching significance (at the 0.1 level) for sheet and box only.

The reason for this might be the following: All object types were uniformly scaled along all three axes by the same factor (n × 1.04 or n × 0.96), resulting in equal relative steps in volume for each scaling step. But since the basic stick measured only 0.5 cm in diameter and was 50 cm long, the only parameter that changed perceivably was its length. The basic sheet was only 0.5 cm thick but 50 wide and 30 cm high, resulting in a more easily recognizable change in overall size for each scaling step compared to the stick. For the box, the noticeably changing depth is added. These added cues seem to result in a lower variance of mean estimation values, finally yielding a higher F-value, as differences of the mean values between high and low system lag settings are similar across object types.

4.6 Real-to-real estimations

In the real-to-real setting, estimations have been fairly accurate with a comparatively low variance, except for the sheet estimation in the low system lag group. Additionally, no significant differences between high and low system lag groups have been detected for any of the objects. This was expected due to the identical viewing conditions. These results suggest that when comparing real objects, participants were able to relate perceived object sizes to those memorized beforehand correctly. Thus, estimation errors in our real-to-virtual experiments are due to virtual environment perception, not due to difficulties to remember and compare object sizes at all. It cannot be ruled out though that the relatively small number and narrow size range of real objects to choose from in the real-to-real task (five objects) might have diminished the variance of size estimations. In the real-to-virtual experiment, the virtual object sizes to choose from where not limited.

5 Conclusion

In the experiment described in this paper we analysed the effects of system lag variation on size perception in a high-end projection-based virtual reality system. The virtual objects were calibrated in real space. This enabled us to compare the actual projected size of the virtual objects with participants' corresponding estimates. Without the calibration, a possible scaling bias caused by the tracking or projection system could not have been excluded.

We reported three main findings:

(1) In the condition enabling the most accurate estimations (low system lag), participants systematically underestimated the sizes of the virtual objects.

(2) Increasing the system lag made participants perceive the virtual objects significantly bigger. We offered a possible explanation for this effect based on a proposed temporal cognitive averaging process of changing size cues. The changing of size cues is suggested to be a combined effect of (a) participants' motion relative to the virtual objects, (b) the system lag, and (c) participants' proposed selective attention for those parts of the virtual objects the line of sight is currently moved to.

(3) Finally we found that the variations of participants' size estimations exhibited a significantly stronger dependence on their rate of movement for high system lag

compared to the low lag condition. As movements were not restricted (which corresponds to an everyday application setting), this resulted in a higher estimation variance in the high system lag setting.

From our point of view, system performance will continue to be a topic to be concerned about even using the latest and most powerful virtual reality computing technology. Thus, we hope that our results can help designing VE applications that successfully support practical tasks. Thorough understanding of size and distance perception is essential for the effective use of many of today's and future VE applications. A lot more research work in the field of size and distance perception is though necessary. Findings so far published in the relatively small number of studies are not coherent. To get a more precise picture of the involved effects is not only interesting and important for the scientific community. It will be needed for virtual environments to gain further importance in various application fields as well.

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References

Bortz, J. (1989). *Statistik für Sozialwissenschaftler*. Berlin: Springer.

Bullinger, H.-J., Riedel, O., & Breining, R. (1998). Perception in Different IPT-Systems. In: *Proceedings of the 2nd International Immersive Projection Technology Workshop, Iowa 1998.*

Cutting, J. E., & Vishton, P. M. (1995). Perceiving Layout and Knowing Distances: The Integration, Relative Potency, and Contextual Use of Different Information about Depth. In W. Epstein & S. Rogers (Eds.), *Perception of Space and Motion* (pp. 69-117). San Diego: Academic Press.

Eggleston, R. G., Janson, W. P., & Aldrich, K. A. (1996). Virtual reality system effects on size-distance judgement in virtual environments. In *Proceedings of the IEEE Conference – Virtual Reality Annual International Symposium (VRAIS) '96*, 139-146.

Ellis, S. R., & Menges, B. M. (1997). Judgement of the Distance to Nearby Virtual Objects: Interaction of Viewing Conditions and Accommodative Demand. *Presence: Teleoperators and Virtual Environments*, 6(4), 452-460.

Gillam, B. (1995). The perception of spatial layout from static optical information. In W. Epstein & S. Rogers (Eds.), *Perception of space and motion* (pp. 23-67). San Diego: Academic Press.

Henry, D., & Furness, T. (1993). Spatial perception in virtual environments: Evaluating an architectural application. In *Proceedings of the IEEE Conference – Virtual Reality Annual International Symposium (VRAIS) '93*, 33-40.

Surdick, R. T., Davis, E. T., King, R. A., & Hodges, L. F. (1997). The Perception of Distance in Simulated Visual Displays: A Comparison of the Effectiveness and Accuracy of Multiple Depth Cues Across Viewing Distances. *Presence: Teleoperators and Virtual Environments*, 6(5), 513-531.

Waller, D. (1999). Factors affecting the perception of interobject distances in virtual environments. *Presence: Teleoperators and Virtual Environments, 8(6)*, 657-670.

Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence: Teleoperators and Virtual Environments, 7(2)*, 144-167.