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PART I: General Issues in the Design and Use of Virtual and Adaptive Environments

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Visual Perception of Egocentric Distance in Real and Virtual Environments

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Even after decades of research, visual space perception remains the subject of active investigation, indicating that it is indeed a challenging problem. Even at a functional level, we are still far from fully understanding some fundamental issues, such as the mapping between physical and visual space (visually perceived space), the connection between visual space and action, and which aspects of visual stimulation are most important in determining the structure of visual space. In the absence of a functional-level understanding, it is hardly surprising that our understanding of the underlying physiological mechanisms lags further behind. Nowhere is our lack of understanding more apparent than when one attempts to synthesize realistic virtual environments using computer graphics; most challenging in this regard is making large-scale vistas and structures appear as immense as their real-world counterparts.

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The primary interest in visual space perception, at least through most of its history, has been with its phenomenology—why the visual world appears the way it does. Within this context, visual space is the visually based component of the phenomenal world, which is the totality of conscious experience (Brain, 1951; Koffka, 1935; Loomis, 1992; Russell, 1948; Smythies, 1994). Research on the structure of visual space and the processes underlying it has been pursued both for its own sake and out of the belief that visual space is a primary determinant of spatial behavior. The most sustained and concerted effort to understand the phenomenology of visual space can be found in the research of Walter Gogel, and the broadest exposition of this understanding can be found in two of his more recent works (Gogel, 1990, 1993).

In the last couple of decades, two lines of research have begun to challenge the assumption that consciously experienced visual perception is causally linked to action. The first of these is research within the ecological tradition, initiated by James Gibson (1958, 1966, 1979) and subsequently pursued by many others (e.g., Flach & Warren, 1995; Lee, 1980, 1993; Turvey, 1977; Turvey & Carello, 1986; Turvey & Remez, 1979; Warren, 1990; Warren & Wertheim, 1990). A widespread assumption within this tradition is that it is possible to understand spatial behavior in terms of control by very specific aspects of visual stimulation (e.g., the pattern of global radial outflow associated with observer translation) without the need to posit any mediating internal representation, such as visual space. The second of these is research showing that the processes underlying certain forms of action appear to be distinct from those processes giving rise to consciously experienced visual space (e.g., Bhalla & Proffitt, 1999; Bridgeman & Huemer, 1998; Bridgeman, Kirch, & Sperling, 1981; Creem & Proffitt, 1998; Goodale & Humphrey, 1998; Milner & Goodale, 1995; Proffitt, Bhalla, Gossweiler, & Midgett, 1995; Weiskrantz, 1986, 1990). Although these two lines of research indicate that a consciously experienced 3-D representation of nearby objects may not be necessary for the control of certain types of action, other research indicates just the opposite (e.g., Philbeck & Loomis, 1997; Philbeck, Loomis, & Beall, 1997).

If future research reveals that much of spatial behavior is not controlled by conscious visual perception, then the rationale for investigating the phenomenology of visual space will be substantially undermined. Without prejudging the outcome, however, we are confident that phenomenology will continue to remain an important topic, if only for its intrinsic interest. Moreover, developers of virtual environments will wish for a better understanding of the topic, for the perceptual realism of virtual environments is of great importance to users in a wide variety of applications involving entertainment, architecture, aesthetics, social interaction, and more. Accordingly, much of the rest of this chapter is concerned with consciously experienced visual perception, with an emphasis on distances beyond the 2-m limit of "personal space" (Cutting & Vishton, 1995).

PERCEPTUAL VARIABLES AND THEIR COUPLINGS

An important perceptual variable in any theory of visual space is that of perceived location, which in turn comprises the perceptual variables of perceived direction and perceived egocentric distance, both of which are defined with the observer as origin. Another variable, perceived exocentric distance, usually refers to the perceived separation of two points along a common visual direction (Foley, 1980; Gogel, 1977, 1990) but can be generalized to refer to the perceived separation between any two points in visual space. There is evidence indicating that perceived separation is determined by more than just the perceived locations of the points defining the exocentric interval (e.g., Foley, Ribeiro-Filho, & Da Silva, 2001; Gogel, 1977; Levin & Haber, 1993; Loomis, Da Silva, Philbeck, & Fukusima, 1996). Other important perceptual variables are perceived size, perceived shape, perceived object motion, and perceived displacements of the observer. Gogel's "theory of phenomenal geometry" takes perceived direction, perceived egocentric distance, and perceived displacements of the observer as its primitives, with these other variables being derivative (Gogel, 1990, 1993).

Throughout much of the history of visual space perception, it has been recognized that certain perceptual variables covary with one another (Epstein, 1982; Gogel, 1984; Sedgwick, 1986). This coupling may sometimes be the result of joint determination by common stimulus variables that naturally covary, but there is evidence that variation in one perceptual variable can directly affect the value of another perceptual variable (Epstein, 1982; Gogel, 1990, 1993; Oyama, 1977) even in the absence of any stimulus change (e.g, in objects that sometimes undergo spontaneous depth reversals; Turner & Braunstein, 1995). Similarly, it is likely that this coupling occurs in the total absence of visual stimulation, as in visual hallucinations (Zubek, Pushkar, Sansom, & Gowing, 1961).

The best-known coupling is that between perceived size and perceived egocentric distance and is referred to as the size–distance invariance hypothesis (Gilinsky, 1951; Kilpatrick & Ittelson, 1953; McCready, 1985; Sedgwick, 1986). As depicted in Fig. 2.1a, size–distance invariance is the relationship between perceived size (S') and perceived egocentric distance (D') for a given visual stimulus of angular size α, as expressed by this equation:

$$S' = 2D' \tan(\alpha/2) \qquad (1)$$

(In generalized versions of size–distance invariance, the constant 2 in Equation 1 is replaced by an observer constant, and the physical value of α is replaced by a perceptual value, α'.)

Another coupling of perceptual variables occurs when either a stimulus object or the observer translates. In this case, perceived displacement of the target

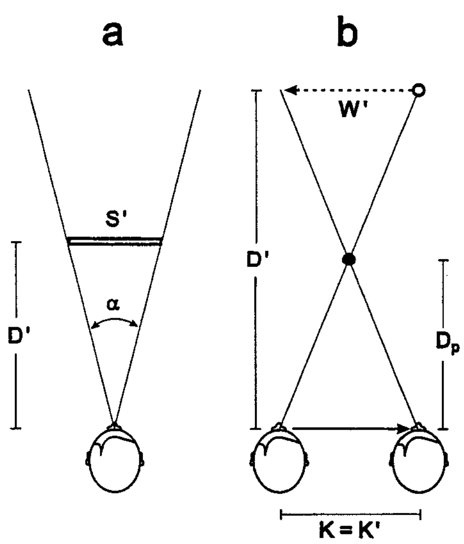

FIG. 2.1. (a) The size–distance invariance hypothesis. A visual stimulus of angular size α, when perceived at a distance D', appears to have a size S'. (b) The apparent distance–pivot distance hypothesis. A stationary point stimulus at pivot distance D_p will appear to move as the head moves if its perceived distance D' is different from its pivot distance. Here, the target is depicted as appearing at a distance D', which is twice D_p. Assuming that the perceived displacement (K') of the head is equal to the physical displacement (K), the target in this case will appear to move through a distance of W' in a direction opposite to the head.

is coupled to its perceived egocentric distance, according to the apparent distance–pivot distance hypothesis (Gogel 1982, 1990, 1993; Gogel & Tietz, 1992). Gogel has treated the general case at length, but to simplify the exposition here, we consider the special case of a translating observer and a stationary target point (Fig. 2.1b). Thus, if an observer's head translates smoothly through a distance K as the observer views a point at pivot distance D_p and the observer perceives the head displacement correctly (i.e., K' = K), the point will appear to move smoothly through a displacement of W' when it is perceived to be at a distance D', according to the following equation:

$$W' = K'(1 - D'/D_p) \qquad (2)$$

So, for example, if the point appears to be twice as far away as its pivot distance (i.e., $D' = 2\,D_p$), it will appear to move through a displacement equal to the perceived head displacement, but in a direction opposite to the head ($W' = -K'$). Besides this simple case of a single-point stimulus, Gogel (1990) has shown how this analysis applies to 3-D reversible objects, like a concave mask that appears convex. In this case, depth reversal of the mask, which is presumably the consequence of an observer tendency to see facelike objects as convex, results in apparent motion of the stationary mask concomitant with translation of the observer's head. Gogel's analysis of motion perception under conditions of observer translation is highly relevant for understanding perception and performance in virtual environments, for misperception of distance ought to result in misperception of the motion (or lack thereof) of virtual objects that are simulated to be moving or stationary while the observer is in motion.

EFFECTIVENESS OF DISTANCE CUES

A great deal of research has been concerned with the effectiveness of the various distance cues in contributing to the perception of egocentric and exocentric distance (for review and analysis, see Baird, 1970; Cutting & Vishton, 1995; Foley, 1980; Gogel, 1977; Howard & Rogers, 2002; Sedgwick, 1986). To see how different cues might contribute differently to space perception, it is instructive to consider the consequence of rescaling a rich environment consisting of many surfaces and objects, such that an observer's eye receives exactly the same projective imagery before and after the rescaling. An example would be monocularly viewing a town from a stationary helicopter at an altitude of 200 m and monocularly viewing a perfect 1/100 scale model of the same from an altitude of 2 m, provided that the spatial distribution of illumination is also appropriately scaled. It is evident that all of the various static perspective cues relating to spatial layout (relative size, texture gradient, linear perspective, height in the field, and shading) are invariant with the rescaling, and therefore uninformative about scale (and egocentric distance). To the extent that these perspective cues are effective in specifying perceived layout, they must do so independently of scale (Loomis & Philbeck, 1999). If the eye translates through space at a speed proportional to the scale (i.e., in eye heights/sec), the resulting optic flow (motion parallax) is also informative about the shape of the layout but uninformative about its scale. Aerial perspective (change in the clarity and color of objects due to scattering within the intervening medium) increases with distance and is thus informative about scale, but not invariantly so because atmospheric conditions (haze, fog, etc.) greatly influence the degree of aerial perspective. The oculomotor cues of accommodation and convergence are absolute distance cues, but are only effective within several meters and thus do not permit the discrimination of larger scale environments. Binocular disparity, which results from the fixed lateral separation of the two eyes, is a relative distance cue, but it does depend on scale; only in conjunction with absolute distance cues can it specify exocentric distance along a line of visual direction (Foley, 1980). Its effectiveness, however, in contributing to the perception of metric distance is limited probably to no more than 100 m, although it must contribute to the perception of depth order well past 200 m.

From the foregoing, it is clear that when there are no constraints on the observer's viewing circumstances (e.g., altitude unknown, speed unknown, atmospheric conditions unknown), the observer has no information about absolute scale other than that provided by the oculomotor cues and binocular disparity (at smaller scales). Conversely, when certain assumptions are met, more can be known about scale and distance. For example, under the assumption that a familiar object is of normal size, its angular size can, in principle, be used to establish its egocentric distance. Similarly, if the observer is viewing an object on the ground plane from normal eye height, height in the field (angular elevation) of the object can, in principle, be used to infer its egocentric distance (Sedgwick, 1986) and, by size–distance invariance, its size. Alternatively, the object's vertical angular extent relative to the horizon can be used to determine its size (Sedgwick, 1980, 1986). Finally, if the observer knows his or her translational speed, the absolute motion parallax of an object known to be stationary can, in principle, be used to determine the object's size and distance.

Although some research has investigated the effectiveness of these various cues (e.g., familiar size: Gogel, 1976; Gogel & Da Silva, 1987; angular elevation: Ooi, Wu, & He, 2001; Philbeck & Loomis, 1997; vertical extent in relation to the horizon: Wraga, 1999a, 1999b; absolute motion parallax: Beall, Loomis, Philbeck, & Fikes, 1995; Ferris, 1972; Gogel & Tietz, 1979; Philbeck & Loomis, 1997), the extent to which these cues determine perceived egocentric distance is still far from settled.

FOCAL AWARENESS, SUBSIDIARY AWARENESS, AND PRESENCE IN VIRTUAL ENVIRONMENTS

An important issue relevant to perception in virtual environments concerns the observer's awareness of the virtual environment as a representation. Both Pirenne (1970) and Polanyi (1970) have treated this issue at some length in the context of representational paintings and photographs; by extension, their analysis also applies to television and cinema. These artifacts, like other forms of representation, have a dual character—they are both objects in 3-D space and representations of other 3-D spaces. When the observer has visual information about the location and orientation of the picture surface, the observer has "focal awareness" of the represented scene and "subsidiary awareness" of the picture surface (Polanyi, 1964, 1970). There is evidence that awareness of the 2-D picture surface interferes with the perceived three-dimensionality of the represented scene (Pirenne, 1970); in particular, a small depiction of a large object results in a perceived object of intermediate size. Perhaps for this reason, it is much easier to induce a perception of very large objects in large-projection displays than in the typical CRT display (Yang, Dixon, & Proffitt, 1999). Besides the perceptual conflict between the depicted scene and the representing medium, there is evidence that when one is viewing a 3-D scene, the suggestion that one is instead viewing a depiction, as conveyed by a surrounding "picture frame," reduces the amount of perceived depth within the scene (Eby & Braunstein, 1995).

Virtual desktop systems that use conventional CRTs are like pictures and paintings in that the CRT surface is well localized in space by the observer. As such, the perceptual and cognitive awareness of the display qua display is likely to conflict with the intended awareness of the represented environment (Yang et al., 1999). The use of a restrictive aperture in conjunction with monocular viewing (Smith & Smith, 1961) or the use of stereoscopic display techniques can greatly reduce awareness of the display surface, thus reducing the perceptual conflict. The use of immersive virtual displays further reduces awareness of the display surface. One way of achieving immersion is the CAVE technique, in which the observer in enclosed within a cube of multiple screens projecting stereoscopic imagery. The more common technique is the use of head tracking in conjunction with head-mounted displays (HMDs). HMDs virtually eliminate all visual cues about the location and orientation of the constituent displays (e.g., LCDs or CRTs) so that the only visual cues available to the observer are those about the represented environment. Either way, immersion technology gives the observer the impression of being surrounded by the computer generated. This sense of immersion, especially when coupled with realistic imagery and a high degree of interactivity between the observer and the virtual environment, promotes "presence" or the experience of "being in" the virtual environment (Barfield, Zeltzer, Sheridan, & Slater, 1995; Heeter, 1992; Held & Durlach, 1992; Lombard & Ditton, 1997; Loomis, 1992; Slater, Usoh, & Steed, 1994; Zahorik & Jenison, 1998). As noted by Loomis (1992), complete presence is tantamount, in Polanyi's analysis, to complete focal awareness of the simulated environment (i.e., with no subsidiary awareness of the virtual display system). As Yang and colleagues (1999) have demonstrated with their experiments on the vertical–horizontal illusion, perception of virtual environments under conditions of minimal subsidiary awareness is subject to exactly the same analysis as perception of real environments.

MEASURING PERCEIVED EGOCENTRIC DISTANCE IN REAL ENVIRONMENTS

Visually perceived location and its constituents, perceived direction and perceived egocentric distance, are aspects of conscious experience. As such, they cannot be measured directly. Instead, measurement can proceed only from a theory that relates measures based on observers' responses to the phenomenological variables of interest. Given the widespread belief that visual direction is perceived quite accurately, most of the research has centered on the measurement of perceived egocentric distance. Even today, this effort likely remains the biggest challenge in the field of visual space perception.

Measures of perceived egocentric distance are wide ranging. The most straightforward and easiest to obtain are those based on direct judgment of perceived distance and a subsequent response that reflects that judgment. Most common are procedures based on numerical estimates. Here the observer estimates the distance either in familiar distance units (e.g., feet or meters) or as a multiple of some given perceived extent and then communicates the resulting estimate (e.g., by speech or keyboard input to a computer). Verbal communication of numerical judgments that are expressed in familiar units of measurement is referred to as verbal report.

Another common direct estimation method involves expressing the estimate by way of some open-loop motor behavior, such as reaching without sight of the hand to the perceived visual location of a target or walking without vision to the location of a previously viewed target. Numerical estimation requires that observers have internalized the unit of measurement, and motoric responding assumes that the response is calibrated to perception, at least over some limited range of distance. Equally important for the validity of these methods is the assumption that the observer's responses are driven by perception alone, uncontaminated by what the observer knows (Carlson, 1977; Gogel, 1976). This assumption, especially in connection with numerical estimation, is likely not to be true in general. For example, objects seen from a great distance appear undersized, but an observer, when asked to report the objective size and distance of a familiar object, can still provide reasonably accurate estimates using knowledge and inference, instead of perceptual appearance (Gogel & Da Silva, 1987). However, when familiar size is eliminated as a cue, there is more reason to believe that verbal reports are informative about perceived distance (e.g., Da Silva, 1985; Foley et al., 2001; Loomis, Klatzky, Philbeck, & Golledge, 1998; Philbeck & Loomis, 1997), but circumspection is always warranted.

Open-loop motoric responding has been extensively used for measuring visually perceived distance in real environments. Some of the earliest uses were in connection with very short distances (ball throwing to targets within a room: Smith and Smith, 1961; pointing to targets within arm's reach: Foley, 1977, 1985; Foley & Held, 1972). More recently, *visually directed action* by a locomoting observer has come into use for the measurement of larger perceived egocentric distances. One of these, mentioned above, involves walking to a previously perceived target without further perceptual information about its location. The results of such experiments under full-cue viewing generally indicate the absence of systematic error when walking to targets up to 20 m away (Elliot, 1987; Elliot, Jones, & Gray, 1990; Loomis, Da Silva, Fujita, & Fukusima, 1992; Loomis et al., 1998; Rieser, Ashmead, Talor, & Youngquist, 1990; Sinai, Ooi, & He, 1998; Steenhuis & Goodale, 1988; Thomson, 1980, 1983). The results of many of these experiments are summarized in Fig. 2.2; the data of the different experiments have been displaced vertically for purposes of clarity.

It might be thought that the finding of accurate performance is not the result of accurate perception of egocentric distance but is simply a consequence of the calibration process accompanying everyday perceptual–motor activity. A problem with this calibration hypothesis is that observers rarely walk blindly to previewed targets more than 3 m away. Stronger evidence against the calibration hypothesis

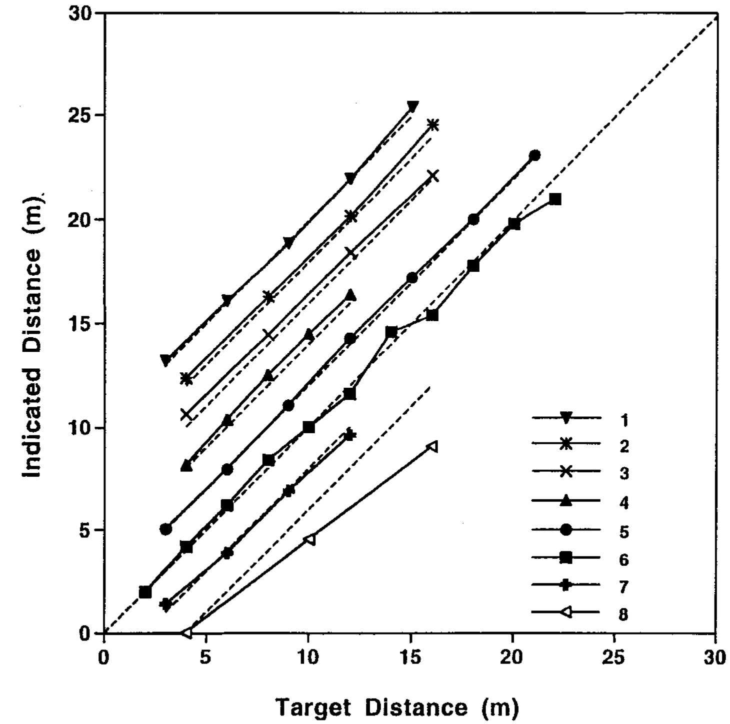

FIG. 2.2. Summary of results using visually directed walking. The data from the different studies have been displaced vertically for purposes of clarity. The dashed line in each case represents correct responding. Sources: (1) from Elliott (1987), (2) average of two groups of observers from Experiment 1 of Loomis et al. (1998), (3) from Experiment 2b of Loomis and colleagues (1998), (4) from Experiment 1 of Loomis et al. (1992), (5) from Thomson (1983), (6) from Rieser and colleagues (1990), (7) from Steenhuis and Goodale (1988), and (8) from Experiment 2a of Loomis and colleagues (1998).

comes from experiments in which the observer's response is less tightly coupled to the target distance. In one such experiment, Thomson (1983) showed the observer a target on the ground ahead, after which the observer began walking toward it without vision. At some unpredictable location during the walk, the observer was signaled to stop and then throw a bean bag the rest of the way to the target. Even with such a two-component response, observers performed with nearly the same accuracy as when walking the full distance.

Other evidence against the calibration hypothesis comes from research using triangulation methods. In *triangulation by pointing* (Fig. 2.3a), the observer views a target and then walks blindly along an oblique path while attempting to continue pointing in the direction of the previously viewed and now imaginally updated target (Fukusima, Loomis, & Da Silva, 1997; Loomis et al., 1992). The terminal

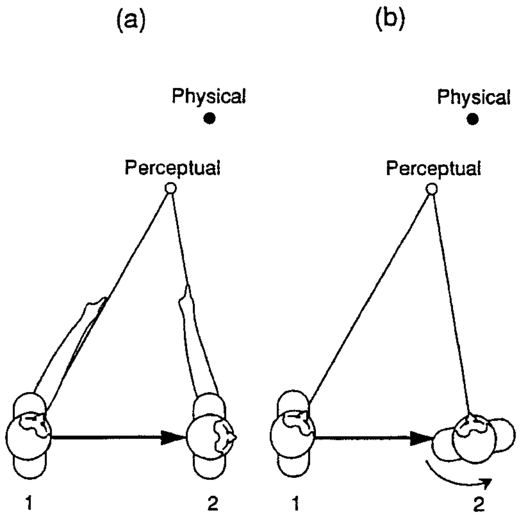

FIG. 2.3. (a) Triangulation by pointing. The observer points at the target with eyes open while standing at Location 1 and then translates with eyes closed to Point 2 while updating the image of the previously viewed target. The pointing direction of the arm at Point 2 can be used to triangulate the position of the initially perceived target under the assumption that the only error in the terminal pointing direction is associated with initial perception of the target. (b) Triangulation by walking. The observer looks at the target with eyes open while standing at Location 1 and then translates with eyes closed to Point 2 while updating the image of the previously viewed target. The observer's terminal heading (or terminal walking direction after a turn toward the target at Point 2) can be used to triangulate the position of the initially perceived target under the assumption that the only error in this terminal heading (or walking direction) is associated with initial perception of the target. (Adapted from Fig. 1 in Fukusima, Loomis, & Da Silva, 1997, (p. 87)).

pointing direction is used to triangulate the initially perceived target location and, hence, its perceived distance from the viewing location. In *triangulation by walking* (Fig. 2.3b), the observer views a target and also then walks blindly along an oblique path. At some unanticipated location, the observer is instructed to turn and face the target (Knapp, 1999) or begin walking toward the target (Fukusima et al., 1997). The terminal heading (facing direction) or course (travel direction) after the turn is used to triangulate the initially perceived target location and, hence, its perceived distance from the viewing location. In another variant of triangulation by walking, the observer walks blindly along an oblique path, turns on command, and then attempts to walk the full distance to the target (Loomis et al., 1998; Philbeck, Loomis, & Beall, 1997). Because the directional responses of the observer toward the target, following a traverse along an oblique path, are not likely to have been previously calibrated by open-loop behavior, the evidence is strong that observers

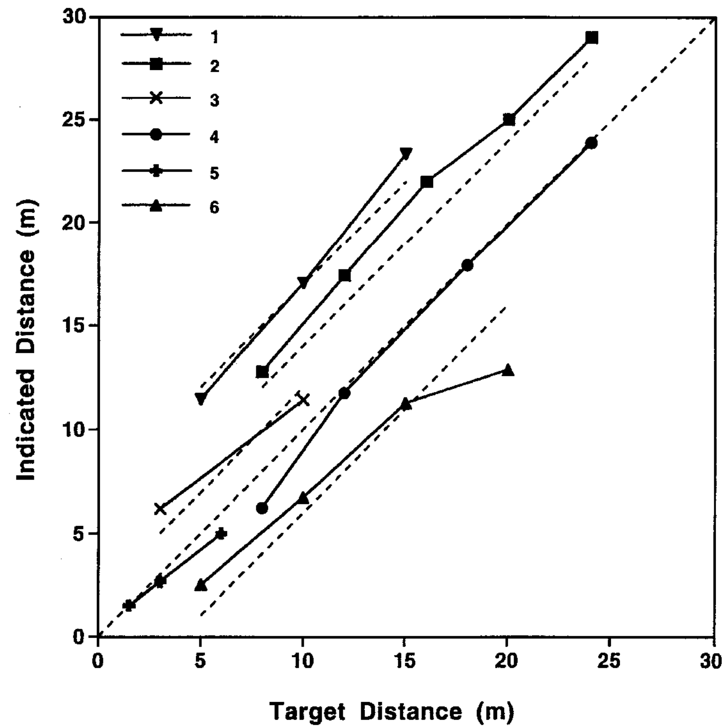

FIG. 2.4. Summary of results using triangulation by pointing, triangulation by walking, and walking along direct and indirect paths to the perceived target, all obtained under full-cue conditions. The data from the different studies have been displaced vertically for purposes of clarity. The dashed line in each case represents correct responding. Sources: (1) from the outdoor experiment on triangulation by walking of Knapp (1999), (2) average of two conditions from Experiment 3 (triangulation by walking) of Fukusima and colleagues (1997), (3) from Experiment 3 (direct and indirect walking) of Loomis and colleagues (1998), (4) average of two conditions from Experiment 4 (triangulation by walking) of Fukusima and colleagues (1997), (5) from the experiment on direct and indirect walking by Philbeck and colleagues (1997), and (6) average of two conditions from Experiment 2 (triangulation by pointing) of Fukusima and colleagues (1997).

accurately perceive visual target distances up to at least 15 or 20 m away, as can be seen in the summary of results in Fig. 2.4.

If these measurements based on visually directed action are indeed reflecting perceived egocentric distance, they ought to result in a pattern of systematic error when distance cues are diminished, as observed using other methods (e.g., Gogel & Tietz, 1979). Philbeck and Loomis (1997) compared verbal report and visually directed walking under different conditions of distance cue availability. Self-luminous targets of constant angular size were viewed in either a dark or a

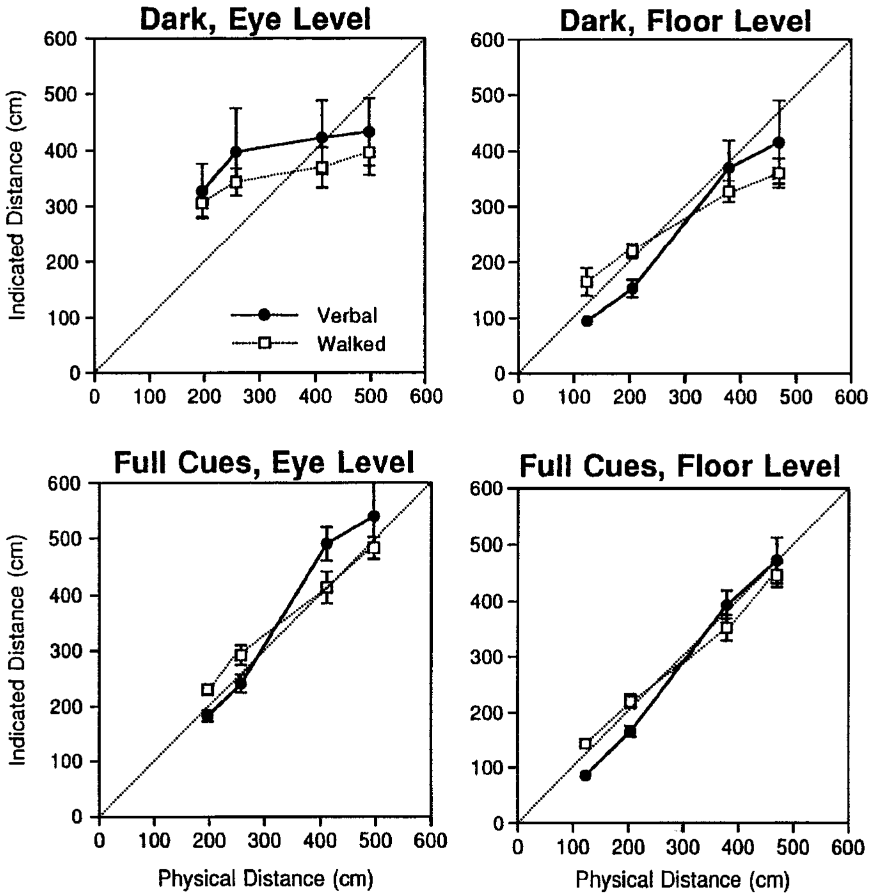

FIG. 2.5. Mean indicated distance (using verbal report and visually directed walking) as a function of target distance in four different viewing conditions. Error bars represent standard error of the mean. (Reprinted from Philbeck & Loomis, 1997).

lighted room (full cues) and were positioned either at eye level or on the ground, the latter condition providing the cue of angular elevation. The results are shown in Fig. 2.5 and support a number of conclusions: (1) the similarity of verbal and motoric responses, (2) accurate responding under full cues, and (3) the importance of angular elevation for egocentric distance perception, as evident in the comparison of the two darkroom conditions.

Out of concern that numerical estimation procedures are subject to contamination by what the observer knows or can infer about target position, Gogel and his associates have developed "indirect" procedures for measuring perceived

egocentric distance (Gogel, 1976, 1979; Gogel & Newton, 1976). These indirect measurements involve the observer judging perceptual variables other than perceived egocentric distance, variables thought to be less subject to cognitive intrusion. The first of these procedures involves the judgment of object size and the size–distance invariance hypothesis, discussed earlier (also see Fig. 2.1a). Under this hypothesis, Equation 1 indicates that if the perceived size, S', of a visual stimulus of angular size α is judged by an observer, perceived egocentric distance, D', can be solved for. The second indirect procedure involves the judgment of perceived motion and the apparent distance–pivot distance hypothesis, also discussed earlier (also see Fig. 2.1b). Under this hypothesis, Equation 2 indicates that if the perceived displacement, W', of a point stimulus is judged by an observer whose head undergoes a displacement of K, the perceived egocentric distance, D', can be solved for, provided that K' (perceived head displacement) is equal to K. Gogel, Loomis, Newman, and Sharkey (1985) performed an experiment evaluating the congruence of the two measures of perceived egocentric distance. In a full-cue laboratory situation, they independently manipulated binocular and motion parallax cues, among others, thus producing variations in perceived distance from about 1 to 3 m. Figure 2.6 shows the computed measures of D' using the two different response measures, averaged over observers, for a variety of target stimuli

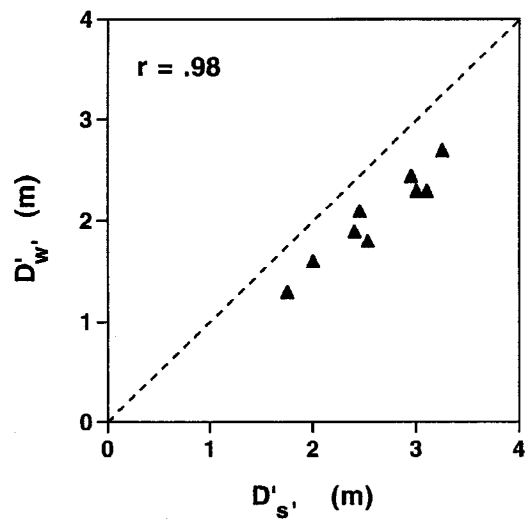

FIG. 2.6. Congruence of two indirect measures of perceived egocentric distance, one based on perceived size (S') and the other based on perceived displacement of a target (W') during a lateral movement of the head. The data points represent different combinations of distance cues. (Source: Fig. 5 from Gogel, Loomis, Newman, & Sharkey, 1985, (p. 24)).

varying in terms of the manipulated distance cues. As can be seen in the figure, the two different procedures resulted in estimates of D' that were highly correlated ($r = .98$); however, the estimates based on size were approximately 20% larger than those based on perceived displacements. Lest it be thought that the two judgments were really of the same perceptual variable, the reader should note that perceived size judgments grow in magnitude as the perceived target moves away from the observer (Fig. 2.1a), whereas judgments of perceived displacement grow in magnitude as the perceived target moves away from the pivot distance of the target (Fig. 2.1b). The congruence of the two measures of perceived egocentric distance is a small part of the strong empirical base supporting Gogel's theory of phenomenal geometry (Gogel, 1990).

The common observation that a very distant object tends to look much smaller than it is physically is consistent with the size–distance invariance hypothesis when the object is perceived to be much closer than it is (Gogel & Da Silva, 1987). Contrasting with this is the geometric analysis of Sedgwick (1980), showing that the vertical extent of an object resting on the ground, when judged relative to the visible or implicit horizon, provides information about its actual size. For example, the top of an object, which is equal in height to the observer's eye height, will coincide with the visible horizon; similarly, an object twice as high as the observer's eye height will extend as much above the horizon as its base lies below. This optic rule for judging height implies that judged object size ought to be invariant with egocentric distance; this would seem especially so for objects that are the same size as the observer's eye height, for optical coincidence between object's top and the visible horizon unambiguously specifies constant size. Yet, objects viewed from very far away appear very much smaller even under these conditions. It would thus appear that using angular height of an object to judge its size, while grounded in the rules of perspective, fails to determine perceived size. It is precisely for reasons such as this that Gogel and his colleagues have developed indirect measures of perceived egocentric distance that are more immune to cognitive intrusion.

How then do the various methods of measuring perceived egocentric distance, of which these are the primary ones, agree with one another, especially in connection with egocentric distances beyond several meters? Da Silva (1985) has reviewed the results of many studies on perceived distance in indoor and outdoor environments. However, none of these studies involved direct comparisons of the different methods mentioned above. Given the huge variation in target distances, visual context, and method, the variable results make generalizations about distance perception difficult.

As mentioned earlier, Philbeck and Loomis (1997) found that verbal report and visually directed walking were in quite close agreement in terms of mean values of perceived egocentric distance (Fig. 2.5), with the verbal reports exhibiting slightly greater variability. Loomis and colleagues (1998) observed the same result for larger target distances (out to 16 m) in an outdoor environment, both for visual perception and auditory perception. Although these two studies indicate that verbal report and visually directed action result in similar estimates of perceived egocentric distance, it is unlikely that the two responses always tap the same judgmental process. Clearly, verbal estimation is appropriate in some situations where visually directed action is nonsensical. For example, an observer is likely to find it reasonable to estimate the depicted distance of an object seen in a photograph viewed normally, whereas the same observer would find it unusual to be asked to perform a visually directed action with respect to the object.

The indirect procedures discussed above have yet to be used for measuring perceived egocentric distance of targets at large distances in natural environments. Gogel's "head motion procedure" has so far only been studied in the laboratory for short egocentric distances; it remains to be seen whether it can be extended to measurement of much larger distances using larger excursions of the head than used until now (50 cm or less). The indirect procedure using judgments of size seems somewhat more promising given that prima facie it should be applicable to all target distances. However, making judgments of size in the context of natural outdoor scenes seems likely to engage cognitive processing nearly to the same extent as direct estimation of egocentric distance does, thus possibly defeating the very intent of it as an indirect method.

PERCEPTION OF VERY LARGE SCALE

Closely related to the perception of egocentric distance is the perception of scale. The difference is one of emphasis, with egocentric distance being associated with a single target and scale being associated with an entire scene. The issue here concerns the basis on which an observer perceives the difference between a complex visual scene and copies of the scene varying only in terms of scale. In particular, we raise the very puzzling question of what perceptual and cognitive processing is involved when a person experiences immensity in the visible environment. When we view a huge object within a natural scene (e.g., the Eiffel Tower, the St. Louis Gateway Arch, or El Capitan in Yosemite Valley), we are impressed with the enormity of such an object. Even large cloud formations viewed from an airliner (where binocular cues and motion parallax information are useless for specifying scale) can appear immense. Although it is likely that we perceive huge objects as smaller than they actually are, the fact remains that we commonly experience immensity in the natural world. Although the experience of immensity is commonplace, it has been neglected by perceptual researchers, perhaps because, in our everyday stance of naive realism (Loomis, 1992), we simply attribute it to the immensity of the objects themselves. This is, of course, no explanation, and we must instead seek to determine the informational basis leading the observer to such an experience.

The next time that the reader is in the presence of a huge object, observe that the object continues to look immense with monocular viewing and stationary head, even with hands cupped to limit the field of view. These observations raise the question of what stimulus information supports the experience of immensity. If one were to close one's eyes for a moment and a small-scale model were moved into place, would one continue to experience immensity, or would subtle visual cues lead immediately to a different perceptual experience? We do not have the answer to this, but we have done unpublished research on the role of prior visual stimulation on perception of size and have found evidence that observers interpret momentary visual stimulation in the context of an existing perceptual model. However, our work scarcely touches the surface of this interesting question. We raise it here, for it is of fundamental importance to the implementation of effective virtual environments. Although some uses of virtual environments may not depend at all on a proper rendering of scale, the phenomenology of visual space cannot be underestimated in its importance. The aesthetic and affective impact of realistically rendered virtual environments is absolutely vital to their success for many applications. For example, a virtual environment used by the travel industry to give a potential visitor to a destination with expansive vistas needs to convey the impression of its size for maximum impact. Whether virtual displays other than those employing multistory projection scenes (e.g., IMAX theaters) will succeed in doing so is a fascinating scientific question with major implications for commercial uses of virtual environments.

PERCEIVED EGOCENTRIC DISTANCE IN VIRTUAL ENVIRONMENTS

Given the role that visual perception of distance plays in an observer's experience within a visually based virtual environment, it is hardly surprising that this is one of the first topics to have been investigated by virtual environment researchers (Barfield & Rosenberg, 1995; Beall et al., 1995; Ellis, & Menges, 1997; Kline & Witmer, 1996; Knapp, 1999; Rolland, Gibson, & Arierly, 1995; Surdick, Davis, King, & Hodges, 1997; Witmer & Kline, 1998; Witmer & Sadowski, 1998). These studies address a variety of issues, most of which take us beyond our immediate interest in the accuracy with which egocentric distance is perceived. Thus, we focus on a few studies that have measured perceived egocentric distance in virtual environments involving HMDs. Our immediate concern in reviewing this work is with the methodological issue of how to assess the perception of distance and scale in virtual environments. Once we are confident about the methods, we can then use them to evaluate how well different virtual environment implementations convey a natural sense of scale. Given that virtual environment technology, including the rendering software, is constantly improving, only future research will tell us what we can ultimately expect from the technology in affording an accurate perception of distance and scale.

For several years, our laboratory at the University of California at Santa Barbara has been using a high-quality virtual display system developed by Andrew C. Beall and Jack M. Loomis (for a detailed description, see Chance, Gaunet, Beall, & Loomis, 1998). The Virtual Research FS5 HMD has a 44-deg (horizontal) × 33-deg (vertical) field of view in each eye, with 100% binocular overlap. Display resolution in each eye, with input from a Silicon Graphics Indigo2, High Impact graphics computer, is 800 horizontal lines × 486 vertical lines. The field-sequential display provides full-color, stereoscopic presentation with an effective visual acuity of about 20/70 (judging from the angular size of each pixel and informal assessments of letter identification performance). The hybrid head/body-tracking subsystem uses video capture of two lights worn on a backpack to measure torso position and heading and a goniometer (mechanical linkage with potentiometers) to measure orientation of the head in relation to the torso. The tracker allows the observer to walk around within a large room with natural head movements (Beall, 1997). We have taken great care to minimize the end-to-end system lag (down to about 50 msec) and to maximize the graphics update rate (30 Hz in each eye), but 80 msec lag and 15 Hz update rate in each eye are more commonly obtained in environments with the complexity of those in the experiments described below. The sense of presence in many of our virtual environments is very compelling, as judged by the informal comments of over 300 people who have had demonstrations with the system. Here we report the results of two experiments on the perception of distance done as part of Joshua M. Knapp's doctoral dissertation (Knapp, 1999). Both involved binocular viewing of projectively-correct imagery, adjusted for the observers' interpupillary distances and eyeheights.

The first experiment compared three measures of perceived egocentric distance: verbal report, walked distance in a visually directed walking task, and a measure based on perceived size. For two of these measures, the targets were spheres placed on a textured ground plane (tesselated with a base texture pattern) at simulated distances of 1, 2.5, and 4 m. Given that one of the tasks involved walking to the target, the upper limit of 4 m was set by the size of the laboratory. The binocular cues of convergence and binocular disparity and the perspective cues of texture gradient, linear perspective, and angular elevation were all available; motion parallax due to head translations was not available, for observers viewed the targets from a fixed location. Because of the limited vertical field of view of the display, observers had to pitch their heads downward to sense the angular elevation of the target. For the verbal report judgment, the observer judged target distance in units of feet over the ground plane (i.e, not direct line of sight from head to target). For visually directed walking, the observer viewed the target and, when ready, walked with eyes closed to the judged position of the target (the display was also turned off). For the judgment based on perceived size, the observer saw a continuous untextured wall extending 3 m up from the ground in a frontoparallel plane at a distance (measured over the ground) of 1, 2.5, or 4 m. The observer turned a knob that varied the width of a vertically oriented aperture in the wall; the task was to make the aperture appear just passable (i.e., just as wide as the observer's body, measured at the shoulders). This judgment of the passability of an aperture has been shown to be very accurate under full cues in real environments (Warren & Whang, 1987). We took the observer's adjusted simulated width as equal to the observer's perceived body width and

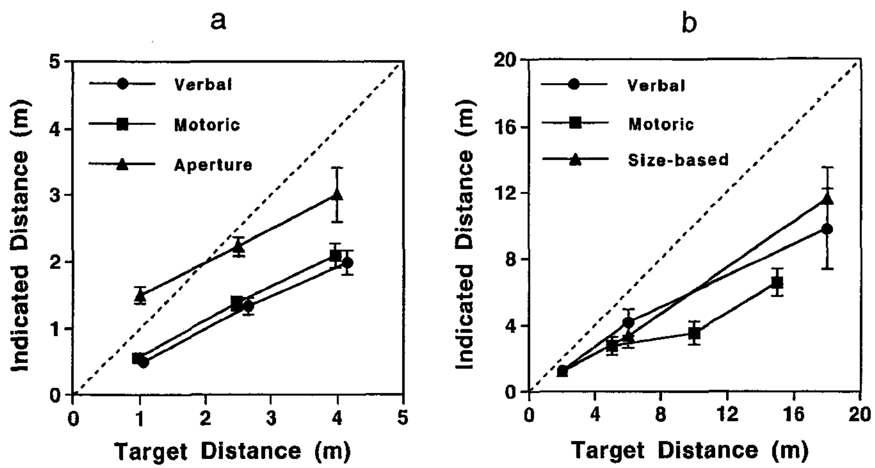

FIG. 2.7. Results of two recent experiments using the University of California at Santa Barbara virtual display system (Knapp, 1999). (a) Comparison of three measures of perceived egocentric distance: verbal report, walked distance in visually directed walking, and a measure derived from adjustment of a visible aperture to match the maximal width of the observer's body. (b) Comparison of three measures of perceived egocentric distance: verbal report, a measure derived from triangulation by walking, and a measure derived from the judgment of perceived size. Error bars represent 1 *SE* of the mean.

used this, in conjunction with size–distance invariance (Equation 1), to obtain an indirect measurement of the perceived distance of the aperture and wall.

Figure 2.7a gives the results of the experiment. Each value of indicated distance (perceived egocentric distance) is based on the mean of the data of 7 observers. Although the aperture-based measure is consistently higher in value than the other two, the three measures all indicate that, for this environment, distance is systematically underperceived, even for these short distances.

The second experiment also compared three measures: verbal report, a measure based on triangulation by walking, and a measure based on perceived size. In contrast with visually directed walking, this triangulation response allowed us to obtain perceived estimates for much larger target distances because walking was in a direction orthogonal to the simulated visual target. Again, spheres were simulated as lying on a ground plane with a tesselated texture, this time at distances of 2, 6, and 18 m. Binocular and perspective cues provided information about the distance of the target. For the verbal response, the observers made their judgments in units of feet. For the size judgment task, spheres of constant angular size were used, and the observer judged the sphere diameter and verbally reported in units of inches. The verbal estimates were converted to perceived distance (over the ground) using size–distance invariance (Equation 1). For the triangulation response, the observer faced the target with the body turned in the direction of the subsequent walking response (as in Fig. 2.3b). When ready to respond, the observer closed the eyes

and initiated the walk until told to stop. After a distance of 3.1 m, the observer, still with eyes closed, turned to face the previously viewed and imaginally updated target. We used the terminal heading of the body (and head) to triangulate the initially perceived location of the target, from which we computed the perceived egocentric distance of the target.

Figure 2.7b gives the results of this second experiment. Each value of indicated distance is based on the mean of 7 observers in the triangulation condition and 10 observers in the other two conditions. The concordance of the three measures is strong evidence that they are all measures of perceived egocentric distance and is also additional support for the idea that action (here, triangulation by walking) is controlled by conscious perception. As with the previous experiment (Fig. 2.7a), the results clearly indicate that egocentric distance is underperceived by a factor of about 2. This is surprising, for the environments in both experiments employed all of the known distance cues that are available to an observer in a natural outdoor environment when viewing from a fixed location.

Results indicating more accurate distance perception in a virtual environment are those reported by Witmer and Sadowski (1998) and replotted in Figure 2.8a. They compared visually directed walking to real targets in a long corridor to visually directed walking (on a treadmill) to virtual targets within a simulated corridor. The indicated distances for the real environment mirror those summarized in Figure 2.2. The indicated distances for the virtual environment, although systematically lower, are still much more accurate than those obtained in our experiments (Fig. 2.7). Also, Witmer and Kline (1998) conducted a similar experiment, this

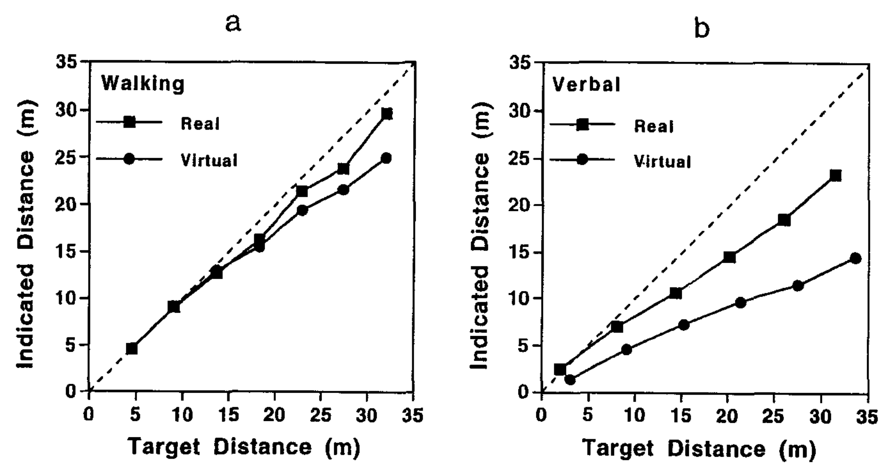

FIG. 2.8. Results of two experiments by Witmer and his colleagues. (a) Indicated distance (putatively perceived egocentric distance) as measured by visually directed walking in real and virtual environments. Walking in the virtual condition was performed on a treadmill. (Source: Fig. 2 from Witmer & Sadowski, 1998, (p. 483)). (b) Indicated distance (putatively perceived egocentric distance) as measured by verbal report in real and virtual environments. (Source: Fig. 3 from Witmer & Kline, 1998, (p. 155)).

time obtaining verbal reports. These data are replotted in Fig. 2.8b. These results for the virtual environment are closer to what we have obtained (Fig. 2.7). As a possible reason for the apparent difference between our results for the virtual environments and those of Witmer and colleagues, we note that their and our visual displays differed in terms of field of view. They used a head-tracked stereoscopic display (Fakespace Labs BOOM2C) with a 140-deg (horizontal) × 90-deg (vertical) field of view, in contrast with our 44-deg × 33-deg field of view. Kline and Witmer (1996) found that limiting the field of view had a large effect on variation in judged egocentric distance (see also Psotka, Lewis, & King, 1998). However, the head was not free to rotate in the Kline and Witmer study, which might have made display field of view more critical in their experiment than in the more usual situation, in which the head is free to rotate. Consistent with this interpretation, Knapp (1999) studied visually directed walking to targets in a full-cue outdoor environment and compared normal unrestricted field of view with a field of view that was restricted by goggles and approximately matched to the head-mounted display used in our virtual environment experiments. Observers performed very accurately in both conditions, with no significant difference between the two. Thus, it appears that the field of view of our head-mounted display is not the reason for underperception of distance in our virtual environments. We have hypothesized that the more likely reason is that the rendering of the scenes used in our experiments is lacking subtle but important visual cues (e.g., natural texture, and highlights). Supporting our hypothesis are some informal observations we have made—real environments, when viewed with our head-mounted display as it is driven by two video cameras located at a fixed vantage point, appear much more realistic in terms of distance and scale than our computer-synthesized virtual environments. If this hypothesis were to be correct, it would mean that photorealistic rendering of the surfaces and objects in a simulated environment ought to produce more accurate perception of distance, including the perception of very large scale. However, a recent study by Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, and Beall (submitted) found that distance in photorealistic virtual environments was perceived no more accurately than it was in more artificially appearing virtual environments. Obviously, more research is needed to determine the stimulus and cognitive factors that underlie this difference in distance perception between real and virtual environments.

SIGNIFICANCE OF DISTANCE PERCEPTION FOR APPLICATIONS OF VIRTUAL ENVIRONMENTS

There are two important reasons why visual distance perception in virtual environments needs to closely mimic visual distance perception in real environments. The first concerns spatial behavior. Users who acquire a skill in one setting will be able to effortlessly transfer this skill to the other setting with a minimum of recalibration

and relearning. The second concerns phenomenology. Virtual environments that look real in terms of scale will generally have a much greater aesthetic, cognitive, and emotional impact. No truer is this than in connection with the rendering of large-scale landscapes and objects. If virtual environment technology eventually succeeds in evoking the same experience of immensity and awe that one feels when viewing the Grand Canyon or the Egyptian Pyramids in person, it will have achieved what large-screen projection techniques of today can only begin to elicit at great expense.

CONCLUSION

In this chapter, we have noted the importance of phenomenological aspects of visual space for virtual environment applications while acknowledging recent research questioning the role that visual space might play in the control of spatial behavior. We have also noted the dual aspects of representational media and the relevance of this for understanding virtual environments. We have treated at some length the very difficult issue of how to measure perceived egocentric distance and have reviewed some of the research on the perception of egocentric distance, both in real and virtual environments. In view of the importance of the topic for virtual environments and the early stage of virtual environment technology, it is clear that much more research is needed to understand the perception of egocentric distance and scale in real and virtual environments, understanding that will undoubtedly further the development of more realistic and effective virtual environments.

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