The perception of egocentric distances in Virtual Environments - a Review

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Over the last 20 years research has been done on the question of how egocentric distances, i.e., the subjectively reported distance from a human observer to an object, are perceived in virtual environments. This review surveys the existing literature on empirical user studies on this topic. In summary, there is a mean estimation of egocentric distances in virtual environments of about 74% of the modeled distances. Many factors possibly influencing distance estimates were reported in the literature. We arranged these factors into four groups, namely measurement methods, technical factors, compositional factors, and human factors. The research on these factors is summarized, conclusions are drawn, and promising areas for future research are outlined.

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1. INTRODUCTION

Egocentric distance, i.e., the subjectively perceived distance from a human observer to an object, is frequently reported to be shorter in virtual than in real environments. This review surveys the current state of research on the topic and aims to provide an up-to-date overview for researchers and practitioners. Today, there is a wide range of applications of virtual environments. For example, virtual environments are used to visualize protein structures [Akkiraju et al. 1996], or to display and even interact

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with architectural [Frost and Warren 2000], train [Seron et al. 2004], or car models [Buxton et al. 2000]. Furthermore, virtual environments are employed for the analysis and design of manufacturing systems [Yang et al. 2011] and the training of military personnel [Loftin et al. 2004] or firefighters [Backlund et al. 2007]. While a veridical spatial perception is not necessary for all applications, for some the correct perception of modeled distances and object sizes is fundamental. To name just two examples, walking through a virtual architectural model would be pointless if the dimensions of structures and rooms could not be perceived as intended. Likewise, for the use of virtual reality in ergonomic evaluations veridical spatial perception is crucial. Besides its significance for some applications, veridical distance perception can be regarded as an indicator for user acceptance [Loomis and Philbeck 2008] and the plausibility and fidelity of a virtual environment.

In the literature, egocentric distance, i.e., the distance from one's self, is differentiated from exocentric distance, which is the distance between two objects lying on different lines of sights. This review surveys the literature on the perception of egocentric distances in virtual environments and suggests a grouping of influencing factors. Nevertheless, to provide the background for comparison we will first summarize the research on distance perception in real environments.

1.1. Distance perception in real environments

The following section provides a brief overview of the research on visual distance perception in real environments, which is not attempting to be exhaustive, though. For a more thorough review on distance perception in real environments see, for example, Creem-Regehr and Kunz [2010], Cutting and Vishton [1995], Loomis and Philbeck [2008], or Proffitt and Caudek [2002].

1.1.1. Basics of visual distance perception. Reflected light from the objects in the environment reaches the eye through the pupil, is bent when passing through the cornea and lens, and reaches the retina. The result is an upside-down two-dimensional image on the retina, which can only be perceived in color and high resolution in the small foveal area. How is it possible to perceive three-dimensional space from this image? A variety of so called depth cues, i.e., sources of information about the spatial relations of the objects in the environment, are used by the human visual system. There are many slightly differing lists of depth cues; we oriented ourselves on Cutting and Vishton [1995].

Depth cues contained in a motionless scene like an image are called pictorial [Goldstein 2007]. Cutting and Vishton [1995] name five of them: occlusion, relative size, relative density, height in the visual field, and aerial perspective. If one object partially occludes another object, the occluded object is seen as farther away than the occluding object. Naturally, occlusion only indicates relative, not absolute distance, but is effective over the whole range of perceivable distances [Cutting and Vishton 1995]. Relative size describes that the farther an object is away, the smaller is the retinal image. Similarly, clusters of objects have a higher retinal density when they are farther away. Relative density is on the margin of utility. Relative size, on the other hand, can yield absolute distance information, if the size of the object is known and it is useful over the whole range of perceivable distances [Cutting and Vishton 1995]. Relative size and relative density also explain the usefulness of ground texture for distance perception, which was first noted by Gibson [1950]. More recently, He et al. [2004]; Sinai et al. [1998]; Wu et al. [2004] demonstrated that a wide expanse of continuous and homogeneous-textured ground surface is helpful for veridical distance perception. Furthermore, Wu et al. [2004] showed that the surface information is integrated via a near to far ground scanning. The depth cue height in the visual field, also called horizon-distance relation

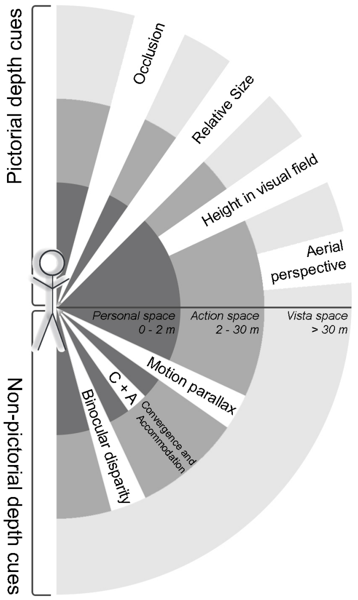

Fig. 1. Schema of effective ranges of the different depth cues (based on Cutting and Vishton [1995]).

or angle of declination, suggests that when both observer and object stand on a ground plane, distance to the object can be computed as a function of the observer's eye height and the angle between the line of sight to the horizon and line of sight to the object [Rand et al. 2011]. If eye height is known, height in the visual field yields absolute distance information from about two meters on, but its effectiveness diminishes with distance [Cutting and Vishton 1995]. Aerial perspective describes that objects in the distance are bluer and decreased in contrast. This depth cue provides only relative distance information and its effective range varies with weather conditions.

As opposed to pictorial depth cues, non-pictorial depth cues are additional sources of distance information deriving either from motion (motion parallax), the oculomotor system (convergence and accommodation), or the fact that humans have two eyes (binocular disparity). When an observer moves, the retinal images of stationary objects off to the side of the direction of movement move as well; the farther the object the slower the movement. This motion parallax is an important depth cue for shorter distances, but its effectiveness declines with distance [Cutting and Vishton 1995]. As the eyes move inward to look at nearby objects, the angle between the optical axes of the eyes decreases, which is called convergence. The change in the curvature of the lens of the eye allowing it to focus on objects at various distances is called accommodation. Convergence and accommodation are naturally linked but dissociable cues. The visual system gets information from the muscles which control convergence and accommodation, thus they can serve as depth cues. Assuming knowledge of, or familiarity with the interpupillary distance (IPD), these cues combined are very effective depth cues up to about three meters [Cutting and Vishton 1995] with convergence being the more effective of the two [Goldstein 2007]. Since each eye views the environment from a different position, the images on each retina differ slightly. The difference in the images in the left and right eye is called binocular disparity and is considered to be the strongest depth cue [Cutting and Vishton 1995; Proffitt and Caudek 2002]. Using random-dot patterns, Julesz [1971] has shown that it is possible to perceive depth with no other depth cue than disparity. For binocular disparity to provide absolute distance information the IPD must be known [Cutting and Vishton 1995], or the information otherwise be scaled [Proffitt and Caudek 2002]. Its effectiveness is highest in the near-field and diminishes linearly with distance.

Concluding from the different effective ranges of the depth cues, Cutting and Vishton [1995] divided the environment in three circular regions around the observer, called personal space, action space and vista space (see Figure 1). Several models have been proposed to explain how the information from different depth cues is integrated, but none of them is able to account for all the empirical findings [Proffitt and Caudek 2002], thus cue integration ”has proven to be a tough problem” [Proffitt 2008, p.180].

1.1.2. Influence of context and personal variables. While the research on depth cues has a long tradition, more recent studies suggest that distance perception might not only be influenced by the availability and reliability of depth cues but also by environmental context and personal variables. These studies are outlined below.

From the research on depth cues one could infer that all other aspects of the environment should be irrelevant for distance perception. However, recent studies challenge this assumption. The results of Lappin et al. [2006] showed that the accuracy of distance estimates differed between three types of environments (a lobby, a hallway, and an open lawn), although all of them offered many depth cues. Witt et al. [2007] conducted five experiments in indoor and outdoor environments with the space between participant and target kept constant. The results indicate that the space beyond the target, although offering no relevant depth cues, can influence perceived distance. Concluding, these studies suggest that distance perception can be influenced by environmental context.

Another line of research suggests that distance perception depends not only on the environment but also on personal variables of the observer, such as the physiological state or the intention to act. Wearing a heavy backpack, for example, increased distance estimates [Proffitt et al. 2003]. In a series of experiments, Witt et al. [2004] showed that this effect is action-specific. Manipulating the effort associated with walking influenced perceived distance only when observers intended to walk the distance. In another study, objects in personal space appeared closer when a tool was held and thus the object became reachable [Witt et al. 2005]. This effect occurred only when the observer intended to reach for the object. In his review, [Proffitt 2008, p.179] concludes that perception ”is influenced by three factors: the visually specified environment, the body, and the purpose” and is therefore action-specific. Other personal variables proposed to influence distance perception include, for example, activation of the elderly stereotype [Chambon 2009], disgust [Stefanucci et al. 2011], and desire for the target [Balcetis and Dunning 2010]. In summary, these studies suggest an influence of personal variables on perceived distance. However, the interpretation of the findings has been questioned by, for example, Durgin et al. [2009], Hutchison and Loomis [2006], Loomis and Philbeck [2008], and Woods et al. [2009] leading to an ongoing debate, which cannot be described here in full depth.

1.1.3. Measurement methods and performance. The perception of distance has some overt components such as vergent eye movements but mostly remains an observer's inner process that cannot be directly observed or measured. Therefore, to determine how well humans can perceive egocentric distance, a variety of measurement methods have been developed. Roughly, there are three categories of such methods, namely verbal estimates, perceptual matching, and visually directed actions. In the following section, we will describe those methods.

Verbal estimation is a traditional and common measurement method. Here, the participant is asked to verbally estimate the distance in a familiar distance unit or as a multiple of a given extent [Loomis and Knapp 2003]. While verbal estimates are fairly accurate for closer distances, farther distances are underestimated, resulting in a mean fitting linear function with an intercept of 0 and a slope of 0.8 [Loomis and Philbeck 2008]. The obvious advantage of verbal estimates is the straight forward and convenient way of measuring. Disadvantages include possible cognitive influences, i.e., verbal estimates are not only driven by perception, but also by knowledge or deductive reasoning, which might bias the measurement of the proper perceptual process [Loomis and Knapp 2003].

In perceptual matching setups, participants are instructed to match the distance or the size of a target object in comparison to the distance or the size of a reference object, respectively. This method is thought to be less influenced by cognitive factors [Loomis and Philbeck 2008], though distances tend to be slightly underestimated [Creem-Regehr and Kunz 2010; Proffitt 2006]. A variant of perceptual matching is bisection, where participants are to indicate the midpoint of an egocentric distance. At least when the object size is known, bisection estimates are accurate [Rieser et al. 1990].

Visually directed actions are a relatively new category of measurement methods for distance perception [Loomis and Philbeck 2008]. Here, the participant views the distance to the target object, then is blindfolded and performs some kind of action towards the target object. The most often used actions are walking and throwing in action space, and reaching in personal space. Blind walking estimates are quite good without systematic errors up to distances of 25 meters [Loomis and Knapp 2003; Loomis and Philbeck 2008], though individual differences exist and participants' accuracy improves over time [Kuhl et al. 2006a]. However, this accuracy depends on walking speed: If participants are instructed to walk faster than normal, accuracy declines [Rieser et al. 1990; Thomson 1983]. Participants might use a simple strategy for blind walking like, for example, the calculation of necessary steps, which might not only be influenced by perception, but also by cognitive factors. Therefore, triangulation tasks were developed. After viewing the object, participants are asked to rotate in a specific angle and then to walk blindfolded for a short, fixed distance. On a signal they are to stop and turn to the previously seen target. From the indicated angle (either by walking two steps ahead or by a pointing gesture) in the direction of the previously seen target the perceived distance can be calculated. Participants' triangulated blind walking estimates are considerably good up to a distance of at least 20 meters, although they are more variable than blind walking estimates [Loomis and Philbeck 2008]. Also related to blind walking is the method called timed imagined walking. With this measurement method participants are required to view an object, then close their eyes and imagine walking to the object. With a stopwatch they measure how long it takes to walk there in their imagination. Using a baseline of each participant's typical walking speed a distance estimate can be calculated. One of the advantages of this method is that it does not require large space. A disadvantage is that there might be additional variance as humans are not all equal in their ability to fulfill the imagining task. Timed imagined walking has been shown to yield estimates similar to blind walking [Decety et al. 1989; Grechkin et al. 2010; Plumert et al. 2005]. Another variant not requiring overt action is affordance judgment. Participants are asked to indicate if they are capable of performing an action, for example, pass through a gap without rotating their shoulders [Geuss et al. 2010].

It is important to note that recent articles have suggested a distinction between perceived extent and perceived location [Witt et al. 2007]. Thus, some measurement methods might, strictly speaking, measure the perceived location, not necessarily the per-

Table I. Percentage of estimated distance to modeled distance^a (with number of studies) for different measurement methods and virtual reality hardware systems.

	HMD^b	Large screens	BOOM2C^c	Monitor	Total
Verbal estimates	73 (3)	83 (1)	47 (1)	–	70 (5)
Perceptual matching	100 (1)	95 (1)	–	–	97 (2)
Visually directed actions					
Blind walking	73 (24)	–	–	–	73 (24)
Blind treadmill walking	–	–	85 (1)	–	85 (1)
Triangulated blind walking	48 (3)	–	–	–	48 (3)
Indirect triangulated blind walking	99 (1)	–	–	99 (2)	99 (3)
Timed imagined walking	76 (1)	65 (3)	–	–	67 (4)
Total	73 (33)	74 (5)	66 (2)	99 (2)	74 (42)

[a] Percentages are rounded. In case of manipulations, the estimates of the control group were used and in studies with feedback the estimates before the feedback were used.
[b] HMD stands for head mounted display.
[c] BOOM2C is an arm mounted display.

ceived extent. Witt et al. [2007], for example, have shown that results can differ between asking the participant to blindly walk the distance to the perceived location or blindly walk the perceived distance in a different direction. Furthermore, it has been found that the phrasing of the instruction can influence how distance estimates are made [e.g., Woods et al. 2009; Wagner 2006]: The term distance can be interpreted differently. Therefore, it has been recommended to explicitly specify the term in the instruction. With an apparent-distance instruction participants are asked to base their answer on how far away the object visually appears to be, whereas with an objective-distance instruction they are instructed to consider how far away the object really is. While apparent distance is supposed to be purely perceptual, objective distance is thought to be influenced by cognitive factors. There are several other types of instructions. Woods et al. [2009], for example, asked their participants to take nonvisual factors into account and to base their answer on how far away they feel the object is. As the chosen type of instruction can influence distance estimates it is important to report it or even better the literal instruction itself in publications.

In summary, distance estimates vary according to the used measurement method. With an appropriate measurement method, results show that humans are good in perceiving distances in full-cue real environments at least up to 20 meters. When depth cues are reduced, the accuracy of distance perception declines [e.g., Künnapas 1968; Philbeck and Loomis 1997]. If egocentric distances are perceived veridical in full-cue real environments but are frequently underestimated in complex virtual environments, the question arises as to the causes of this difference in performance.

1.2. Getting virtual - a first overview

While egocentric distances are perceived veridical in full-cue real environments, they are frequently reported to be underestimated even in complex virtual environments. Kenyon et al. [2007a] speculated that the underestimation of distances in virtual environments may be due to a variety of factors including hardware errors, software errors and errors of human perception. Such ”depth compression” was even seen as ”inevitable” [Jones et al. 2001, p.44]. Naturally, research in the field of computer graphics has focused on hardware and software aspects. There are a considerable number of studies on factors producing depth distortions and propositions for ideal parameter settings or algorithms for the correction of distortions [e.g., Holliman 2004; Howarth 1999; Kuhl et al. 2009; Masaoka et al. 2006; Wartell et al. 1999]. Articles presenting mathematical models or correction algorithms are not considered in this review, as it is focused on empirical user studies. Further, only research on visual virtual environments is discussed here; for distance perception in auditory virtual environments see,

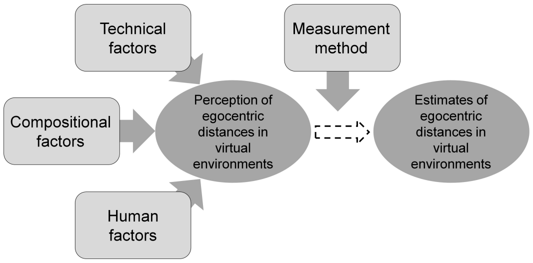

Fig. 2. The four groups of influencing factors on distance perception and distance estimates.

e.g., Kapralos et al. [2008], Loomis et al. [1999], or Zahorik et al. [2005]; for distance perception in visual augmented reality see, e.g., Kruijff et al. [2010] or Swan II et al. [2007].

For the current review psychophysical results from the data bases PsycINFO, PSYNDEX, Web of Science, and Google Scholar were analyzed. Relevant articles were searched with various combinations of the keywords ”virtual reality”, ”virtual environment”, ”virtual”, ”head mounted display”, ”CAVE”, ”egocentric distance”, ”spatial perception”, and ”space perception”. After identifying relevant articles, the references of those were considered, as well as later articles citing them. Included were not only journal articles, but also papers and posters presented at conferences. The search was terminated in August 2012, leading to a total number of 78 articles dating from 1993 to August 2012. In summary, the reviewed articles result in a mean estimation of egocentric distances in virtual environments of 74% of the modeled distances (see Table I). Note however, that from the articles reviewed here only 30 explicitly mention a percentage in the text, a table, or in a chart. The total greater than 30 derives from the fact that several articles report percentages for more than one measurement method, virtual reality hardware system, or experiment.

In the reviewed articles, many factors possibly influencing distance estimates were reported. Therefore, we decided to arrange factors into four groups, namely measurement methods, technical factors, compositional factors and human factors (see Figure 2). These groups were generated pragmatically and are neither theoretically founded nor exhaustive. In the group measurement methods we subsumed a variety of methods used to make the inner process of perception observable. In the group technical factors we concentrated on technologies and their parameters employed to present the virtual environment. The group compositional factors is defined as the virtual environment’s features, e.g., whether there is a floor texture or avatars are present. In the group human factors psychological characteristics are subsumed, e.g., the individual differences between users or how perception changes through adaptation. These four groups form the structure of the review.

2. MEASUREMENT METHODS - APPLYING VIRTUAL PSYCHOPHYSICS

As described above, several methods have been developed to measure subjective distance perception. In the following section we will summarize the methods and their variations used in the reviewed articles. Further, we will discuss their practicability with different virtual reality hardware systems and compare the results obtained with different methods.

Table II. The suitability of the most common measurement methods for different virtual reality hardware systems.

	HMD[a]	CAVE[b]	Large screens	Monitor
Verbal estimates	+	+	+	+
Perceptual matching	+/-	+	+	+
Visually directed actions				
Blind walking	+	-	-	-
Triangulated blind walking	+	+/-	+/-	+/-
Blind reaching	+	+	+	+
Timed imagined walking	+	+	+	+

[a] HMD stands for head mounted display.
[b] CAVE stands for Cave Automatic Virtual Environment.
+ indicates that the method is suitable for the hardware system
+/- indicates that the method is of limited suitability for the hardware system (see text for further explanation)
- indicates that the method is not suitable for the hardware system

2.1. The variety of measurement methods

A number of studies used verbal estimates (mostly in meters or feet). As simple as this method is, there still are different procedures. For example, some authors asked their participants to give verbal estimates with the objects still visible [e.g., Klein et al. 2009; Kunz et al. 2009; Proffitt et al. 2003], while others instructed them to close their eyes first [e.g., Mohler et al. 2006], or close their eyes and turn the head first [Alexandrova et al. 2010]. Perceptual matching tasks were also applied. Some authors asked their participants to match the distance or the size of a target object as compared to a reference object, respectively [e.g., Eggleston et al. 1996; Kenyon et al. 2007b; Li et al. 2011; Sinai et al. 1999]. Others instructed them to indicate the midpoint of a distance [e.g., Bodenheimer et al. 2007], or to indicate which of two objects was closer [e.g., Bruder et al. 2012; Surdick and Davis 1997]. Note however, if both the target and the reference object are virtual, it is –strictly speaking– not a distance perception measurement, but merely a measurement for just noticeable differences. Probably most often used are visually directed action methods with blind walking being the most often applied action. In order to avoid hesitantly walking, different strategies were adopted, e.g., instructing participants to walk without hesitation [e.g., Waller and Richardson 2008], practicing blind walking [e.g., Sahm et al. 2005; Willemsen and Gooch 2002], or indicating the straight direction via a foam pathway [e.g., Waller and Richardson 2008], an acoustic signal [e.g., Grechkin et al. 2010; Nguyen et al. 2008] or by one experimenter walking next to the participant [e.g., Creem-Regehr et al. 2005]. Some studies used a treadmill for blind walking estimates [e.g., Bergmann et al. 2011; Witmer and Sadowski Jr. 1998] in order to allow for using this method in a smaller space, too. Other variations are different kinds of indirect blind walking [Geuss et al. 2012; Lin et al. 2011]. Another often used action is triangulated walking [e.g., Loomis and Knapp 2003; Rébillat et al. 2011; Richardson and Waller 2007; Thompson et al. 2004; Willemsen et al. 2009]; only rarely applied is blind throwing [Ragan et al. 2012; Sahm et al. 2005]. When the viewed objects are within reaching distance, blind reaching has also been used as an action [e.g., Bingham et al. 2001; Napieralski et al. 2011]. Timed imagined walking [Grechkin et al. 2010; Klein et al. 2009; Plumert et al. 2005; Ziemer et al. 2009] and affordance judgments have also been applied [Geuss et al. 2010; Walker et al. 2012].

The choice of a measurement method mainly depends on the hardware system at hand, as not all combinations are suitable (see Table II for an overview). While verbal estimates can be used with all hardware systems, the most often applied method blind walking is only applicable with head mounted displays (HMD) in large rooms or corridors. The alternative method triangulated walking does require less space, but has been shown to be influenced by the participants' knowledge of the room geometry [Klein et al. 2009]. Perceptual matching could be applied with all hardware systems. However, combining HMDs and perceptual matching only allows for comparisons to remembered or virtual reference objects, since HMDs completely block out reality. In summary, the whole range of measurement methods known from research on distance perception in real environments has been adopted for use in virtual environments, but not all methods are suitable for all hardware systems.

2.2. Comparison between measurement methods

A number of studies on distance perception in virtual environments have used two or more methods in the same experiment allowing for direct comparisons. Thereby, some findings from distance perception in real environments have been replicated in virtual environments. As in real environments, blind throwing and blind walking estimates were comparable [Sahm et al. 2005], blind reaching estimates were more accurate and more consistent than verbal estimates [Napieralski et al. 2011], timed imagined walking yielded estimates similar to blind walking [Grechkin et al. 2010; Plumert et al. 2005], and blind walking estimates were generally more accurate than those obtained via triangulated blind walking [Richardson and Waller 2007] or via indirect blind walking [Lin et al. 2011]. However, while in real environments distance estimates gained via visually directed action methods are nearly veridical, in virtual environments distances are generally underestimated nearly independent of the applied measurement method. The exception might be affordance judgments which rather indicate conservative answers or overestimation in both real and virtual environments [Geuss et al. 2010]. However, this technique was adopted only in two studies so far. While distances are underestimated independently of the applied measurement method, the amount of the underestimation can differ between measurement methods [e.g., Klein et al. 2009; Lin et al. 2011; Napieralski et al. 2011; Richardson and Waller 2007].

And further, the effect of an experimental manipulation might be found with one but not with another measurement method. For example, Kunz et al. [2009] showed that while the quality of graphics had no effect on blind walking estimates, it did have an effect on verbal estimates. Likewise, in real environments there are studies reporting differences in the effect of an experimental manipulation on verbal estimates and blind walking estimates [e.g., Andre and Rogers 2006]. This has been interpreted as support of the theory that there are two representations of visual space, a cognitive representation for conscious perception and a sensorimotor representation for action [e.g., Bridgeman et al. 2000; Goodale and Milner 1992; Parks 2012]. This theory is the subject of an ongoing theoretical debate [e.g., Creem-Regehr and Kunz 2010; Loomis and Philbeck 2008]. Alternative explanations include task-specific selection of visual information for task-specific representations or different postperceptual judgment processes after forming one common representation [Kunz et al. 2009].

In summary, underestimations in virtual environments are consistently present regardless of the method applied. Considering all the specific advantages and disadvantages of the different measurement methods, it is not possible to single one method out as best for further studies. Instead, it seems advisable to choose a visually directed action method (apart from affordance judgments) according to the used hardware system as those yield good estimates in real environments and are the most often applied methods which makes the results more comparable. When possible, verbal estimates could be used in addition to the visually directed action method to account for the possibly existing different representations for action and perception.

3. TECHNICAL FACTORS - CONSTITUTING VIRTUAL ENVIRONMENTS

One of the main differences between real environments and virtual environments is that virtual environments are not perceived unmediated, but through a virtual reality hardware system. This can have several implications like, for example, a restricted field of view (FOV), weight on the head, missing or distorted non-pictorial depth cues, less depth cues through low rendering quality, or distortions of the stereoscopic image through deviating parameter settings or optical lens systems. Studies on whether and to what extent these factors influence distance perception are summarized in the following section (see Table III for an overview of studies on technical factors).

3.1. Hardware

Since the vast majority of research concerning distance perception in virtual reality was done using HMDs, an obvious hypothesis is that underestimations are caused by physical properties of the HMD like the restricted FOV, the weight on the head or wearing a helmet itself. The influence of these factors was tested in real environments. In two studies, restricting the FOV did not significantly influence distance estimates if head movements were allowed [Creem-Regehr et al. 2005; Knapp and Loomis 2004]. A mock HMD matching not only the FOV but also the mass and moments of inertia of a real HMD led to significant underestimations though less than those usually found in virtual environments [Willemsen et al. 2004]. An inertial headband on the other hand that only replicated the mass and moments of inertia of an HMD while not restricting the FOV did not yield significant underestimation [Willemsen et al. 2009]. Two research groups replaced the mock HMD with an HMD equipped with optical see-through functionality that is usually used for augmented reality. Therefore, participants wore an HMD and still saw the real environment. No significant underestimations were found [Grechkin et al. 2010; Jones et al. 2008, 2011]. Note however that Grechkin et al. [2010] reported underestimations for blind walking estimates when two overestimating participants were excluded as outliers and that Jones et al. [2011] reported that the cover of their HMD was not completely sealing. Not in a real but using a virtual environment, Jones et al. [2012] showed that distance estimates were significantly better with an HMD with a diagonal FOV of 150° as compared to a restricted diagonal FOV of 60°. In summary, the cited studies suggest that the FOV restriction caused by an HMD is in itself not the cause for the underestimation, but combined with the mass and moments of inertia of the HMD and the feeling of wearing a helmet, the HMD hardware does account for a certain amount of the distance underestimations found in virtual environments presented in HMDs.

While most researchers examining virtual distance perception have used HMDs, there have been other studies employing stereoscopic desktop monitors [e.g., Holliman et al. 2007; Rosenberg 1993; Roumes et al. 2001], a mechanical arm mounted display called BOOM2C [Witmer and Kline 1998; Witmer and Sadowski Jr. 1998], nonstereoscopic large screens [e.g., Alexandrova et al. 2010; Plumert et al. 2005; Ziemer et al. 2009], stereoscopic large screens [e.g., Armbrüster et al. 2008; Luo et al. 2009; Paillé et al. 2005], and Cave Automatic Virtual Environments (CAVE; Cruz-Neira et al. [1992]) [e.g., Kenyon et al. 2007a; Klein et al. 2009; Murgia and Sharkey 2009; Pollock et al. 2012]. Unfortunately, there are only five studies presenting the same virtual environment via different hardware that allow for a comparison between them. Of these five, two studies reported an influence of hardware on distance perception. Klein et al. [2009] demonstrated that distances were underestimated more when the virtual environment was presented on a large tiled display as compared to a CAVE condition. The authors attributed this to the wider FOV in the CAVE. Naceri et al. [2010] found that participants were better in comparing the distances to two virtual objects when presented on a stereoscopic widescreen display as compared to an HMD. On the other hand, there are two studies showing equal distance perception in different hardware setups [Grechkin et al. 2010; Riecke et al. 2009] and one reporting no statistical tests [Combe et al. 2008]. From the above cited studies, all using different measurement methods, virtual reality hardware systems, and virtual environments it is impossible to conclude a consistent pattern of hardware influences on distance perception. However, it can be ruled out that underestimations in virtual environments are limited to a specific system as they are reported in all hardware systems.

3.2. The availability of non-pictorial depth cues

As described above, the non-pictorial depth cues motion parallax, convergence, accommodation, and binocular disparity are important for perceiving distances. In virtual environments, motion parallax is only given when the movements of a user are tracked. There are studies with conflicting results concerning the question of whether the additional depth information from motion parallax is helpful for estimating distances. On the one hand, Creem-Regehr et al. [2005] showed that restricting head rotation in a real-world indoor environment seen through a limited FOV leads to significant underestimation. However, this might not be due to missing motion parallax but rather due to the prevention of near-to-far ground scanning, which was shown to be important for distance perception of objects on the ground plane [Wu et al. 2004]. On the other hand, two studies found no influence of motion parallax: Jones et al. [2008] instructed the participants to either stand still or sway back-and-forth while viewing a real hallway, a real hallway through a see-through HMD or a virtual model of the hallway in an HMD. Surprisingly, they reported small underestimations in all conditions. An explanation presented by Jones et al. [2011] was that the HMD cover was not completely sealing. Similarly, Luo et al. [2009] compared three motion parallax conditions in a CAVE. In the control condition the participants were not allowed to move their heads, in the passive condition motion parallax was generated by the virtual environment while in the active condition participants were instructed to move their head in a standardized way. There was no effect of the motion parallax variations. One study did not report any statistical tests after comparing a condition with head tracking to a condition without head tracking [Combe et al. 2008]. Beall et al. [1995] also did not report statistical tests, but concluded that motion parallax is a weak depth cue for real and virtual nearby objects. Results from research in real environments indicate that motion parallax is helpful for perceiving distances if only few or no other depth cues are available [e.g., Ferris 1972; Gogel and Tietz 1979], but offers little additional information if binocular disparity is present [Bradshaw et al. 2000; Watt and Bradshaw 2003]. Further, motion parallax is considered only a weak depth cue beyond two meters [Philbeck and Loomis 1997]. In summary, there is no empirical evidence that providing motion parallax improves distance perception in virtual environments. Consequently, missing or distorted motion parallax is likely not the cause for the underestimation. Nevertheless, head tracking is important as it is seen as a component of immersion [Bowman and McMahan 2007; Narayan et al. 2005] and as enhancing presence [Hendrix and Barfield 1995; Schuemie et al. 2001].

Convergence and accommodation are, in normal life, joined together and ”extremely effective in measuring distance”, at least up to a distance of two meters [Cutting and Vishton 1995, p.92]. In stereoscopic virtual reality systems, like a CAVE for instance, users need to accommodate onto the depth of the display or screen plane in order to see objects clearly while the convergence point depends on camera disparity and may be in front, on, or behind the display. Thus, the user’s visual system is confronted with conflicting depth information and might be misguided by the accommodative information. In their list of perceptual issues related to stereoscopic displays, Drascic and Milgram

[1996] therefore included the convergence-accommodation conflict as one of the ”hard problems”. Even though today several technical approaches to solve the problem exist, none of those systems are commercially available yet [Miles et al. 2012]. Evidence for accommodative information as an influencing factor on distance perception in virtual reality comes from a study by Bingham et al. [2001]. They used a relatively simple virtual environment consisting of a dark sphere with green phosphorescent-like dots against a dark background and found that applying -2 diopter glasses to reduce the focal distance significantly decreased distance estimates. On the other hand, Kenyon et al. [2007a] could not find evidence for the influence of accommodative information. They compared a condition with unrestricted viewing to a condition with pinhole apertures and found no significant difference between the two conditions. The authors argue that pinholes render accommodation uninformative and thereby remove the conflicting depth information. However, the method to use pinholes to inhibit accommodative information is questioned [Hoffman et al. 2008; Watt et al. 2005]. Further, there are results showing the influence of accommodative information on 3D shape perception with random dot stereograms [Hoffman et al. 2008; Watt et al. 2005]. In real environments, accommodation is considered to be a weak depth cue [e.g., Palmer 1999; Proffitt and Caudek 2002] and as having little effect on distance perception in full-cue conditions [Mon-Williams and Tresilian 1999, 2000]. However, in case of a conflict between accommodation and convergence, depth perception has been shown to be influenced by accommodative information [Swenson 1932]. In summary, even though accommodation on its own is a weak depth cue in real environments, at least in sparse virtual environments the conflicting accommodative information can influence distance perception. Furthermore, the accommodation-convergence conflict has been shown to cause visual fatigue [e.g., Hoffman et al. 2008; Lambooij et al. 2009; Ukai and Howarth 2008]. Therefore, if possible, long viewing distances and a rich virtual environment containing many other depth cues are recommended [Hoffman et al. 2008], because the influence of the accommodative information declines with distance [Cutting and Vishton 1995] and with decreasing relative reliability [Hoffman et al. 2008].

Binocular disparity has often been pointed out to be the strongest depth cue [Cutting and Vishton 1995], even if its influence can be competed by other depth cues [see, e.g., Hartung et al. 2001; Metzger 2006]. So, the question is whether stereoscopic presentation can improve distance perception as compared to monoscopic presentation. Several studies found no significant difference between distance estimates made in a stereoscopic as compared to a monoscopic viewing condition [Eggleston et al. 1996; Roumes et al. 2001; Willemsen et al. 2008], or made in a binocular as compared to a monocular viewing condition in a real environment [Creem-Regehr et al. 2005; Willemsen et al. 2008]. The results of Luo et al. [2009] are in contrast to those described above. They reported that size adjustments were significantly better in a stereoscopic than a monoscopic viewing condition in a single wall CAVE. In a study of Bingham et al. [2001] the difference between blind reaching estimates did not reach significance, but perceptual matching performance was significantly better in a stereoscopic than in a monoscopic viewing condition. These conflicting results can easily be explained. As described above, the effectiveness of binocular disparity is highest in personal space. Consequently, the studies using shorter distances found an influence while studies using longer distances did not (see Table III). In summary, for shorter distances missing binocular disparity impairs distance perception. However, this does not explain the underestimations occurring under stereoscopic conditions.

3.3. Quality of graphics

The virtual environments employed for the first studies on virtual distance perception were rather elementary. This led Loomis and Knapp [2003] to hypothesize that the observed distance compression might be due to simplicity of the virtual environments. They assumed that distance perception might increase with improvements of the quality of graphics. There are four studies concerning this hypothesis.

Willemsen and Gooch [2002] presented high quality stereo photos of a hallway and a virtual model of the hallway in an HMD; results were equal for both conditions. Similarly, Thompson et al. [2004] found no difference between distance estimates made while presenting stereoscopic panorama images, a simple texture mapped virtual model, or a wireframe virtual model, respectively. However, Kunz et al. [2009] revisited the hypothesis based on different measurement methods. While distance estimates via blind walking were the same for a virtual model of a room presented in an HMD in high-quality and low-quality, verbal estimates were more accurate in the high-quality model. The authors concluded that the quality of graphics influences distance estimates only for verbal responses. Phillips et al. [2009] in turn found that quality of graphics can also influence distance estimates made via blind walking. They presented a high-fidelity virtual model of a room via an HMD compared to a non-photorealistic rendering of the same virtual model similar to wire-frame. The participants were in the real room and were told that the virtual model was a replica of the room they were standing in. In this specific situation distance estimates in the high-quality condition were relatively close to reality, while in the lower-quality condition, distances were underestimated.

In summary, even with all the information the described studies have provided, the hypothesis of the influence of the quality of graphics can neither be rejected nor confirmed. There are two problems with the methodology. First, using stereoscopic panorama pictures as stimuli material for good graphic quality has the shortcoming that even if the pictures would be taken according to the eye height and IPD of every single participant, they still would not offer motion parallax. Second, although results were reported showing that low quality rendering, e.g., wire frame models, only occasionally degraded distance perception, we still cannot rule out that an increase in quality, i.e., realistic shading, texturing, highlights, etc., might improve distance perception. It has already been shown that greater visual realism enhances presence and physiological responses [Slater et al. 2009]. Therefore, studies with state-of-the art high quality graphics as seen in new computer games or computer animated movies would be preferable.

3.4. Geometric distortions

Stereoscopic virtual reality technology seeks to present a true three-dimensional view of a scene to the user, just as she or he would see the scene in the real world. But in the process distortions of the image can occur, for example minification, shear distortion, or pincushion distortion. For some of the distortions correction methods have been suggested [Kuhl et al. 2009]. Here, the question is whether these image distortions influence distance perception. This has been studied for minification and magnification, distorted angle of declination, deviating stereo base, and pincushion distortion.

Since the time of Leonardo Da Vinci, recommendations for images have been made to use a horizontal FOV between 45° and 60° to avoid distortions [Cutting 2003]. In virtual reality technology the virtual FOV, named geometric FOV (GFOV), has to be adjusted to the characteristic of the used hardware. With HMDs this can be difficult as the values in the manufacturers' specifications for the display FOV (DFOV) of the specific HMD can differ from the actual values [Kuhl et al. 2009; Stanney et al. 1998;

Steinicke et al. 2011]. If the GFOV settings do not correspond to the DFOV of the HMD, images are minified or magnified, which was repeatedly shown to influence participants' distance estimates [Bruder et al. 2012; Kellner et al. 2012; Kuhl et al. 2006b, 2009; Steinicke et al. 2011; Zhang et al. 2012]. On the other hand, Walker et al. [2012] did not find a significant influence of the GFOV setting. This might be due to the use of affordance judgments as measurement method. Further, Steinicke et al. [2011] found that if participants are asked to adjust the GFOV to match a virtual model of a room to the formerly seen real room, they set the GFOV larger than the DFOV. Note that this was despite the fact that the authors took great care in measuring the actual DFOV. Kellner et al. [2012] individually calibrated the GFOV for each participant, but still found significant underestimations.

In reality, the height of an object in the visual field located on a flat ground plane is a good depth cue [Cutting and Vishton 1995]. Therefore, a distorted angle of declination might influence distance estimates. A distorted angle of declination can be caused by a camera height that differs from the users' eye height or other deviating camera settings. There are three studies concerning the angle of declination with conflicting results. On the one hand, Messing and Durgin [2005] lowered the horizon 1.5° in a virtual outdoor scene and found that distance estimates were influenced by the manipulation. Similarly, Leyrer et al. [2011] found that varying the height of the camera and therefore the virtual eye height significantly influenced distance estimates. On the other hand, Kuhl et al. [2009] manipulated the angle of declination by varying the pitch index of the virtual camera up or down by 5.7° and found no significant differences. However, since in real environments pitch manipulation with prisms has been shown to have effects [e.g., Gardner and Mon-Williams 2001; Ooi et al. 2001], Kuhl et al. [2009] suggest several explanations for their negative finding and nevertheless recommend careful calibration of the pitch index.

Another cause for distortions might be the use of a standard stereo base instead of a stereo base corresponding to the users' IPD. Drascic and Milgram [1996] stated that even a small deviation of the stereo base from the users' IPD can result in large distortions. Nevertheless, in the application of virtual reality technology it is common to use a smaller stereo base to allow for easier fusion or a greater stereo base to enhance image depth [Wartell et al. 1999]. Robinett and Rolland [1992] called ignoring the variation in IPD one of the most common modeling errors. There are only few and conflicting empirical studies concerning the question, whether a stereo base that differs from the IPD of the user influences distance perception. Rosenberg [1993] asked their participants to align two virtual pegs presented on a stereoscopic display. The stereo base was set at intervals between 0 and 8 cm. The results showed an improvement with an increasing stereo base from 0 to 2 cm, but no additional improvements above a stereo base of 3 cm. With an HMD, Kellner et al. [2012] compared conditions with a fixed stereo base of 6.5 cm to conditions in which the stereo base was individually calibrated and found no significant differences. Similarly, Willemsen et al. [2008] also found no significant difference between a fixed stereo base of 6.5 cm and individually measured IPD (ranging from 5.2 to 7.0 cm) at 5 and 10 meters distance. But at 15 meters distance estimates did differ significantly. Further, Bruder et al. [2012] showed that with a larger stereo base objects were perceived as closer in an HMD.

Because the display screens of an HMD are very close to the eyes, HMDs feature an optical lens system that allows the user to focus as if the screens were farther away and provide a reasonable FOV. However, this lens system also causes distortions, of which the most significant is the radial distortion [Watson and Hodges 1995], often called pincushion distortion [Woods et al. 1993]. This distortion causes the geometry of the image to stretch away from the lens center, which leads to inwardly curved lines. Several authors have developed and described correction methods for the pincushion distortion [e.g., Kuhl et al. 2009; Robinett and Rolland 1992; Watson and Hodges 1995]. Kuhl et al. [2009] designed an experiment to test whether the pincushion distortion affects distance perception. The results showed no significant effect of pincushion distortion on distance estimates.

In summary, pincushion distortion does not seem to influence distance perception. The distortions caused by a deviating stereo base have an influence under some conditions, but further studies are needed. Distortions of the angle of declination, or caused by minification or magnification do influence distance perception. Thus, carefully obtained settings are important. Note however that these distortions alone do not explain the commonly found underestimations in virtual environments because even with careful calibration virtual distances were underestimated.

4. COMPOSITIONAL FACTORS - THE REALITY ASPECT IN VIRTUAL ENVIRONMENTS

In comparison to real environments, virtual environments can be very sparse consisting of only a single presented object or a textured ground and therefore lack pictorial depth cues. In addition, at least in virtual environments presented in HMDs, objects for size comparisons are missing, and particularly the view of the own body is unavailable. Further, in real environments we experience transitions between different environments, e.g., from an indoor to an outdoor environment through a door, but in a virtual scenario the user is typically thrown into the new environment. The following section deals with studies on these factors (see Table IV for an overview).

4.1. The availability of pictorial depth cues

Virtual environments in the research on egocentric distance perception vary strongly in their composition, ranging from very simple ones consisting of only a single presented object in front of a white background over outdoor scenes like a large flat grassland to complex indoor scenes. Therefore, virtual environments differ in the amount of pictorial depth cues they provide. From research in real environments it is known that when depth cues are reduced the accuracy of distance perception declines [Künnapas 1968; Philbeck and Loomis 1997] and severe distortions of distance and size perception can occur as, for example, in the case of the moon illusion [see, e.g., Kaufman and Kaufman 2000]. There are a few studies on the question of whether a lack of pictorial depth cues, low complexity, or the type of environment contribute to the distance underestimation found in virtual environments.

One study directly varied the available depth cues [Surdick and Davis 1997]. On a grayscale monitor in a wheatstone stereoscope a simple virtual environment was presented, consisting of a flat square floating in a room with walls and a floor. The authors compared conditions in which either one of the following depth cues was available or all of them: relative brightness, relative size, relative height, linear perspective, foreshortening, texture gradient, and binocular disparity. The results of the matching task showed that the so called perspective cues (linear perspective, foreshortening, and texture gradient) improved distance perception more than the other cues. The authors concluded that perspective cues might be more important to be included in virtual environments than other pictorial depth cues. Tai [2012] employed various lighting conditions and found a tendency for longer distance estimates in conditions with lower luminance contrast between target and background. However, the author did not report any statistical tests. Thomas et al. [2002] manipulated simple textures and reported that depth matching estimates were better with textures containing vertical lines as compared to textures containing horizontal lines. Several studies tested the influence of different types of floor texture. Witmer and Kline [1998] varied the texture of the floor in their virtual environment, but found no influence of the manipulation. All of the used textures were quite simple and maybe not different enough to influence dis-

Table III. Overview of studies on technical factors.

HMD mechanical properties and restricted FOV

First author	Year	Environment	Measurement method	Hardware[a]	Experimental conditions[a c]	Results[b]
Creem-Regehr	2005	Real hallway	Blind walking	—	FOV of 42°/32° vs. Unrestricted FOV FOV of 42°/32° +no head moves vs. Unrestricted FOV	N.s. Significant
Grechkin	2010	Real hallway	Blind walking Timed imagined walking	—	FOV of 49.5°/40.5° +HMD vs. Unrestricted FOV	Significant N.s.
Jones	2008	Real hallway	Blind walking	—	FOV of 49.5°/40.5° +HMD vs. Unrestricted FOV FOV of 49.5°/40.5° +HMD +no head moves vs. Unrestricted FOV	Significant N.s.
Jones	2011	Real hallway	Blind walking	—	FOV of 49.5°/40.5° +HMD vs. Unrestricted FOV	N.s.
Jones	2012a	Model of a hallway	Blind walking	HMD	FOV of 150° diagonally vs. FOV of 60° diagonally	Significant
Knapp	2004	Real large flat grassy field	Verbal estimates Blind walking	—	FOV of 58°/43° vs. Unrestricted FOV	N.s.
Willemsen	2004	Real room	Blind walking Triangulated blind walking	—	FOV of 47°/38° +mock HMD vs. Unrestricted FOV	Significant
Willemsen	2009	Real room	Blind walking Triangulated blind walking	—	FOV of 47°/38° +mock HMD vs. Unrestricted FOV Unrestricted FOV +inertial headband vs. Unrestricted FOV	Significant N.s.

Comparisons between different hardware

First author	Year	Environment	Measurement method	Hardware[a d e] = Experimental conditions	Results[b]
Combe	2008	Model of a car cockpit	Perceptual matching	HMD, tracked vs. HMD, not tracked vs. Hemi cylindrical screen, not tracked	(no tests)
Grechkin	2010	Model of a hallway	Timed imagined walking	Stereo HMD, tracked vs. 3 right-angled mono screens, not tracked	N.s.
Klein	2009	Model of a grassy field	Verbal estimates Timed imagined walking Triangulated walking	Stereo tiled display wall, tracked vs. Four-wall stereo CAVE, tracked	Significant Significant N.s.
Naceri	2010	Black or white background	Perceptual matching	Stereo HMD, not tracked vs. Stereo widescreen display, not tracked	Significant
Riecke	2009	Photos of a room	Indirect triangulated walking	Mono HMD, not tracked vs. Mono 50" LCD screen, not tracked	N.s.

Availability of non-pictorial depth cues

First author	Year	Environment	Measurement method	Hardware[a e]	Experimental conditions[c]	Results[b]
Beall	1995	Dark background	Verbal estimates	HMD	Motion parallax as depth cue to a real vs. a virtual object	(no tests)
Bingham	2001	Dark background	Blind reaching Perceptual matching	HMD	- 2 diopter glasses vs. No glasses Stereoscopic vs. Monoscopic (arm reaching)	Significant N.s. Significant
Combe	2008	Model of a car cockpit	Perceptual matching	HMD	Tracked vs. Not tracked	(no tests)
Creem-Regehr	2005	Real hallway	Blind walking	—	FOV of 42°/32° +no head moves vs. Unrestricted FOV Binocular vs. Monocular (4-12m)	Significant N.s.
Eggleston	1996	Simple model of hallway crossing	Perceptual matching	HMD	Stereoscopic vs. Monoscopic (3 - 37 m)	N.s.
Jones	2008	Real hallway Real hallway Model of a hallway	Blind walking	— HMD HMD	Swaying vs. Standing still	N.s. Significant N.s.
Kenyon	2007a	Model of table on checkerboard floor	Perceptual matching	Four-wall CAVE	Pinhole apertures vs. No apertures	N.s.
Luo	2009	Model of table on checkerboard floor	Perceptual matching	Single wall CAVE	Active vs. Passive vs. No motion parallax Stereoscopic vs. Monoscopic (1-2.8m)	N.s. Significant
Roumes	2001	Videos of natural outdoor scene	Perceptual matching	Television monitor	Stereoscopic vs. Monoscopic (20-160m)	N.s.
Willemsen	2008	Real university building lobby Model of a university building lobby	Triangulated walking	— HMD	Binocular vs. Monocular (5-15m) Stereoscopic vs. Monoscopic (5-15m)	N.s. N.s.

Quality of graphics

First author	Year	Environment	Measurement method	Hardware[a]	Experimental conditions	Results[b]
Kunz	2009	Model of a room	Verbal estimates Blind walking	HMD	High quality model vs. Low quality model	Significant N.s.
Phillips	2009	Model of a room	Blind walking	HMD	High quality model vs. Wireframe model	Significant
Thompson	2004	Photo vs. Model of a university lobby	Triangulated walking	HMD	Stereo photo vs. Texture mapped model vs. Wireframe model	N.s.
Willemsen	2002	Photo vs. Model of a hallway	Blind walking	HMD	Stereo photo vs. Texture mapped model	N.s.

Geometric distortions

First author	Year	Environment	Measurement method	Hardware[a]	Experimental conditions[f]	Results[b]
Bruder	2012	Model of a hallway	Perceptual matching	HMD	GFOV 0.5 vs. 0.75 vs. 1.0 vs. 1.25 vs. 1.5 of DFOV Stereo base 0.0 vs. 1.0 vs. 2.0 vs. 3.0 vs. 4.0 of IPD	Significant Significant
Kellner	2012	Model of a room	Blind walking	HMD	GFOV larger vs. Smaller vs. Equal DFOV Stereo base equal IPD vs. 6.5cm	Significant N.s.
Kuhl	2006b	Model of a hallway	Blind walking	HMD	GFOV larger vs. Equal DFOV	Significant
Kuhl	2009	Model of a hallway	Blind walking	HMD	GFOV larger vs. Smaller vs. Equal DFOV Camera pitched normal vs. Up vs. Down by 5.7° No vs. Normal vs. Exaggerated pincushion distortion	Significant N.s. N.s.
Leyrer	2011	Model of a room	Verbal estimation	HMD	Camera height equal vs. Lowered vs. Heightened by 50cm	Significant
Messing	2005	Model of outdoor scene	Verbal estimation Blind walking	HMD	Lowered horizon by 1.5° vs. Normal horizon	Significant
Rosenberg	1993	Blue background	Perceptual matching	Monitor	Stereo base of 0 vs. 0.5 vs. 1 vs. 2 vs. 3 vs. 4 vs. 5 vs. 6 vs. 7 vs. 8cm	Partly s.
Steinicke	2011a	Model of a room	Perceptual matching	Monitor	GFOV 0.4 to 1.6 of DFOV	Significant
Steinicke	2011b	Model of a room	Perceptual matching	HMD	GFOV larger vs. Smaller than DFOV	Significant
Walker	2012	Model of a room	Affordance judgment	HMD	GFOV larger vs. Equal DFOV	N.s.
Willemsen	2008	Model of a university building lobby	Triangulated blind walking	HMD	Stereo base equal IPD vs. 6.5cm	Partly s.
Zhang	2012	Model of a room	Blind walking Verbal estimates	HMD	GFOV larger vs. Equal DFOV	Significant N.s.

[a] HMD stands for head mounted display.

[b] Significant indicates a significant difference between distance estimates made in the described experimental conditions; N.s. indicates a not significant difference between distance estimates made in the described experimental conditions.

[c] FOV stands for Field of View with numbers indicating the horizontal and vertical FOV in degrees.

[d] Stereo stands for stereoscopic; Mono stands for monoscopic.

[e] CAVE stands for Cave Automatic Virtual Environment.

[f] GFOV stands for geometric field of view; DFOV stands for display field of view; IPD stands for interpupillary distance.

tance estimates. Sinai et al. [1999] on the other hand found an influence of texture. The participants performed more accurate in the matching task, when the texture of the floor in the virtual environment was a brick pattern as compared to a carpet or grass. The authors argued that it might be that the symmetry of the brick pattern improved distance perception. Similarly, Kenyon et al. [2007b] found that performance in a perceptual matching task was better in a rich cue environment (consisting of a bottle standing on a table, a checkerboard floor, and a horizontal line to a grey sky), as compared to a sparse environment (the bottle only against a grey background). This finding was replicated in two follow-up studies addressing other factors but using the same environments [Kenyon et al. 2007a; Luo et al. 2009]. Consistently, Murgia and Sharkey [2009] showed that adding a lattice design to the environment improved depth perception. Two studies presented different types of environments. Armbrüster et al. [2008] found no difference in distance estimates between three environments called no space (spheres in front of a blue background), open space (spheres on a green floor and a blue sky with some clouds), and closed space (spheres on the floor of a closed gray room). Note however that all the used textures were unicolored and did not offer any texture gradient information and such very little additional depth information. A study by Bodenheimer et al. [2007] reported better matching task performance in a virtual outdoor environment than in a virtual indoor environment. This is in line with the results of Lappin et al. [2006] and Witt et al. [2007] who, as described above, showed in real environments an effect of environmental context which is not yet fully understood.

In summary, the described studies show nearly consistently that, as expected from research in real environments, adding pictorial depth cues or, in more general terms, adding complexity to a virtual environment improves distance perception. Further, they support the environmental context hypothesis and the importance of a regularly structured ground texture as emphasized by several authors for real environments [e.g., Gibson 1950; He et al. 2004; Sinai et al. 1998; Wu et al. 2004]. However, while the lack of pictorial depth cues might account for a certain amount of the underestimation in sparse environments, it does not explain the underestimation in complex virtual environments.

4.2. Adding avatars

HMDs used to present virtual environments are without see-through functionality, thus blocking completely out the real environment including the users' own body. This has been suggested as a potential cause for distance underestimation for various reasons.

Creem-Regehr et al. [2005] suggested that not being able to see one's own feet on the ground could lead to missing information about eye height and thus angular declination. They conducted an experiment in a real-world indoor environment and occluded vision of the participants' feet and floor below the feet to about 1.5m. This manipulation did not influence the distance estimates suggesting that the view of one's own feet is not necessary for accurate distance perception in real environments. Mohler et al. [2008] argued that, nevertheless, the view of one's own body might be helpful in virtual environments to provide a metric and to ground the user in the virtual environment. In their experiment, participants were instructed to look around a virtual environment presented in an HMD either with or without a first-person avatar present. The participants were tracked and the avatar moved according to the tracked movements of the participants. The results showed distance estimates to be significantly better in the avatar condition. Similarly, Phillips et al. [2010] found that a tracked avatar presented in a non-photorealistically rendered virtual replica of the real room improved distance estimates. Further, Mohler et al. [2010] showed that both a tracked and a static avatar improved distance estimates even if the avatar was dislocated. In contrast, in the study by Ries et al. [2009] only a tracked avatar improved distance estimates, while a static avatar and moving spheres at the tracking marker positions did not. The authors concluded that the improvement of distance estimates through avatars is not due to the available size and motion cues but is caused by an enhanced sense of presence. On the other hand, Leyrer et al. [2011], Lin et al. [2011], and McManus et al. [2011] did not find a significant improvement of distance estimates when a tracked avatar was present. McManus et al. [2011] hypothesized that in their study this might be due to the provided mirror and such the possibility to see the avatar's face, the relatively short amount of time participants looked at the avatar, or the tracking method used. The results of Ragan et al. [2012] are not included because they did not report any statistical tests.

In summary, while in some studies distance estimates were improved when an avatar was present, in other studies presenting an avatar had no influence on distance estimates. One possible explanation for these contradictory results was presented by Leyrer et al. [2011]. In their experiment, they found that a tracked avatar improved distance estimates significantly only if ownership was controlled, i.e., the participants' feeling that the avatar was located at the same location as their body and the feeling that the avatar was their own body. This was measured using an after-experiment questionnaire. Thus, an avatar might improve distance estimates only if the user accepts it as the representation of his or her own body and not if the user sees it as an object. The feeling that a virtual body is one's own body is also described as self-presence [Ratan and Hasler 2010] and is thought to enhance the sense of presence [Slater and Usoh 1994]. Despite the relevance of the concept, theoretical and empirical work on self-presence is limited [Aymerich-Franch et al. 2012; Jin and Park 2009]. Since the studies described above did not assess ownership, one can only speculate that the contradictory results might be due to different levels of avatar ownership. Further studies assessing or directly manipulating avatar ownership are necessary to test this hypothesis and answer the question of whether the underestimation can be prevented through substituting the missing view of the body with an avatar.

4.3. Using objects with familiar size, virtual replicas and transitional environments

If the size of an object is known to the observer, absolute distance information is available [Cutting and Vishton 1995]. Thus, an obvious approach to improve distance estimates is to add objects with familiar size to the virtual scene. There are two studies using this approach. Interrante et al. [2008] compared blind walking distance estimates made in a virtual room either with or without faithfully-modeled replicas of familiar objects (tables, chairs, computer monitors). However, although the participants had seen the real furniture previously, results showed that their presence did not improve distance estimates. Similarly, Armbrüster et al. [2008] found that adding a tape measure with white-and-yellow stripes every meter did not improve distance estimates despite the fact that the participants were explicitly told that the tape measure started exactly at their standing position and that each segment was 1 meter in length. In summary, according to these studies, adding objects with familiar size does not seem to improve egocentric distance estimates in virtual environments. This is in line with research in real environments where familiarity with a present object's size has also been shown to have only a weak influence [Beall et al. 1995].

Interrante et al. [2006] went one step further and did not only add familiar objects to an otherwise unfamiliar environment, but used a virtual replica of the room, which the participants had seen before, as the virtual environment. This lead to the interesting finding that participants did not underestimate virtual distances when the virtual environment was an exact replica of the real environment they were currently standing in. This finding was replicated by Phillips et al. [2012]. In a follow-up study participants underestimated distances in both a condition with an enlarged replica and a condition with a shrunken replica [Interrante et al. 2008]. The authors concluded that the participants were not able to use metric information from the real environment to calibrate their blind walking estimates. Instead, the good estimates might be due to a higher sense of presence. Building on these results, Steinicke et al. [2010] tested whether presenting a virtual replica of the actual room and a new virtual environment subsequently would improve distance estimates and found that the so called transitional environment improved distance estimates significantly. In summary, distance estimates are accurate if the virtual environment is a replica of the earlier seen real environment the participants are standing in, the participants are told that it is a replica, and the scale is correct. A transition through this known virtual environment to an unknown virtual environment can also improve distance estimates, which might be due to an enhanced sense of presence. Thus, these findings suggest a low sense of presence as a cause for the underestimation.

5. HUMAN FACTORS - INDIVIDUAL INFLUENCES AND DIFFERENCES

Apart from measurement methods, technical factors, and compositional factors, factors lying within the user like, for example, inexperience with virtual reality or a low sense of presence might affect distance perception in virtual environments. Further, there is research on the approach to counteract the underestimation by adaptation through feedback and practice. Consequently, negative transfer effects to reality after adaptation have also been studied. In the following section, we will summarize the research on these factors (see Table V for an overview of studies on human factors).

5.1. Influence of feedback and practice

At the latest since Stratton [1897] experimented with reversing glasses that turned visual perception upside-down, the great adaptability of the visuomotor system is known. But for adaptation to take place, interaction with the environment via self-produced movements is required [e.g., Held 1965]. So, several studies have dealt with the question, what type of interaction or feedback leads to an improvement in distance estimates in virtual environments.

The first to test if feedback can correct distance estimates in virtual environments were Witmer and Sadowski Jr. [1998]. They asked their participants to open their eyes after they completed the blind treadmill walking estimate. The participants were able to see where the virtual target was in relation to them and thus getting terminal visual feedback about their estimate. However, this feedback had no effect. It might be that 15 trials were not enough to adapt as adaptation increases with the number of interactions [Fernández-Ruiz and Díaz 1999].

In a series of experiments, Richardson and Waller examined the effect of different types of feedback. Explicit feedback in the form of a schematic depiction including the walked distance and the actual distance in meters did improve distance estimates, but mainly for the measurement method it was given for [Richardson and Waller 2005]. Implicit feedback in the form of interaction did also change distance estimates [Richardson and Waller 2007]. The interaction between the pretest and the posttest consisted of walking to targets with vision plus a stop signal. Walking to targets without vision plus an auditory stop signal increased distance estimates to a similar amount, whereas seeing the corresponding optic flow without walking did not [Waller and Richardson 2008]. Analogically, Mohler et al. [2006] reported that walking to targets with vision, terminal visual feedback and walking without vision with an auditory stop signal improved distance estimates in a comparable way, respectively. Further, walking freely through the virtual environment corrected distance estimates as

Table IV. Overview of studies on compositional factors.

Availability of pictorial depth cues

First author	Year	Environment	Measurement method	Hardware[a c]	Experimental conditions	Results[b]
Armbrüster	2008	Unicoloured surfaces	Verbal estimates	Stereoscopic screen	Type of environment (No space vs. Open space vs. Closed space)	N.s.
Bodenheimer	2007	Model	Perceptual matching	HMD	Model of hallway vs. Model of outdoor scene	Significant
Kenyon	2007a	Model	Perceptual matching	Four-wall CAVE	Grey background vs. Model of table on checkerboard floor	Significant
Kenyon	2007b	Model	Perceptual matching	Four-wall CAVE	Grey background vs. Model of table on checkerboard floor	Significant
Luo	2009	Model	Perceptual matching	Single wall CAVE	Grey background vs. Model of table on checkerboard floor	Significant
Murgia	2009	Model	Perceptual matching	Four-wall CAVE	Black background vs. Green lattice	Significant
Sinai	1999	L-shaped room	Perceptual matching	HMD	Green carpet vs. Brick pattern vs. Grass texture	Significant
Surdick	1997	Simple room	Perceptual matching	Monitor	Available depth cues	Significant
Tai	2012	Model of a hallway	Perceptual matching	Monoscopic display	Various lighting conditions	(no tests)
Thomas	2002	Purple background	Perceptual matching	Stereoscopic display	Textures containing vertical lines vs. Horizontal lines	Significant
Witmer	1998	Model of a hallway	Verbal estimates	BOOM2C	No vs. Coarse vs. Fine floor texture Dot vs. Bone texture	N.s. N.s.

Adding avatars

First author	Year	Environment	Measurement method	Hardware[a]	Avatar[d]			
					colocated		dislocated	
					static	tracked	static	tracked
Leyrer	2011	Model of a room	Verbal estimates	HMD	—	N.s.	—	—
Lin	2011	Model of a room	Blind walking Indirect blind walking	HMD	N.s.	N.s.	—	—
Mcmanus	2011	Model of a room	Blind walking	HMD	—	N.s.	—	—
Mohler	2008	Model of a hallway	Blind walking	HMD	—	Significant	—	—
Mohler	2010	Model of a hallway	Blind walking	HMD	Significant	Significant	Significant	Significant
Phillips	2010	Model of a room	Blind walking	HMD	—	Significant	—	—
Ries	2009	Model of a hallway	Blind walking	HMD	N.s.	Significant	—	—

Objects with familiar size, virtual replicas and transitional environments

First author	Year	Environment	Measurement method	Hardware[a]	Experimental conditions	Results[b]
Armbrüster	2008	Unicoloured surfaces	Verbal estimates	Stereoscopic screen	Tape measure present vs. Not present	N.s.
Interrante	2006	Model of a room	Blind walking	HMD	Virtual replica vs. Real environment distance estimates	N.s.
Interrante	2008	Model of a room	Blind walking	HMD	Virtual replica with exact vs. Smaller vs. Larger size Familiar objects present vs. Not present	Significant N.s.
Phillips	2012	Model of a room	Blind walking	HMD	Virtual replica vs. Model of an unfamiliar room	Significant
Steinicke	2010	Model of a room	Blind walking	HMD	Virtual replica as transitional environment vs. Not	Significant

[a] HMD stands for head mounted display.

[b] Significant indicates a significant difference between distance estimates made in the described experimental conditions; N.s. indicates a not significant difference between distance estimates made in the described experimental conditions.

[c] CAVE stands for Cave Automatic Virtual Environments.

[d] Significant indicates a significant difference between a condition with an avatar and a condition without an avatar; N.s. indicates a not significant difference between a condition with an avatar and a condition without an avatar

well [Waller and Richardson 2008]. Recently, Altenhoff et al. [2012] showed that blind reaching estimates improved after visual and haptic feedback while verbal estimates did not. The authors suggest this might be due to different representations for action and conscious perception (see section 2.2).

Jones et al. [2011] found an improvement of distance estimates over time without providing any feedback. In a series of experiments they carefully varied possible external influences on performance, showing that a little gap between the HMD and the participant's face provided enough peripheral information for the participants to adapt. This was replicated by Jones et al. [2012]. Interrante et al. [2006] asked their participants to touch a real table while seeing a virtual table at the same location to test the effect of haptic feedback. After the interaction phase distance estimates were better for longer, but not for shorter distances. Since there was no control group, it remains unclear if this specific improvement was due to the haptic feedback or a mere practice effect as in the study of McManus et al. [2011], in which participants walked longer distances over time although no feedback was provided. This is in line with data analyses showing an improvement in accuracy over time for blind walking estimates in real environments [Kuhl et al. 2006a].

In summary, mere practice can improve distance estimates obtained via blind walking. As in real environments, feedback including an action component leads to adaptation and enhances distance estimates. Therefore, a period of familiarization with the virtual environment before the actual task to correct distance perception has been suggested [e.g., Altenhoff et al. 2012; Waller and Richardson 2008]. This can be a pragmatic solution in some cases. However, most applications of virtual reality require transferability of results, training effects, etc. to real environments. And, for example, as it has been shown, one can easily adapt and learn to throw at a target while wearing prism glasses but will miss the target as soon as the prisms are taken off [e.g., Fernández-Ruiz and Díaz 1999; Martin et al. 1996]. This is called aftereffect [e.g., Fernández-Ruiz and Díaz 1999; Martin et al. 1996], or in the case of virtual environments carry-over effect [Altenhoff et al. 2012] or transfer effect [Witmer and Sadowski Jr. 1998] and might limit the usefulness of feedback and practice as a counteraction to the underestimation.

5.2. Transfer effects to reality and Presence

Aftereffects are seen as an indication that adaptation has occurred [Fernández-Ruiz and Díaz 1999]. Thus, the arising question is how humans perceive the reality after adapting to a virtual environment. Of the studies focusing on the effect of feedback four have also tested for transfer effects to reality. Because adaptation to a virtual environment requires participants to increase their distance estimates, as an aftereffect overestimation of distances in real environments would be expected. And indeed, this has been found in two studies: Waller and Richardson [2008] collected blind walking distance estimates in a real environment before and after virtual interaction. The interaction consisted of walking on a textured ground with posts. After the interaction, participants overestimated real distances and this persisted over all 18 trials. Interrante et al. [2006] had their subjects estimate distances via blind walking in a real room, and afterwards in a virtual replica. After providing haptic feedback, they collected estimates in the virtual replica, then in the real room. They found that the real world distance estimates were longer after experiencing the virtual environment. On the other hand, in the study of Mohler et al. [2006] interaction with the virtual environment led to adaptation but did only change distance estimates in reality, when the authors intentionally doubled optic flow rate. The authors attributed this to the particular form of feedback. Witmer and Sadowski Jr. [1998], whose feedback did not result in adaptation, noticed that participants underestimated real world distances more, when they had estimated distances in a virtual hallway through blind walking on a treadmill first. Similarly, walking on a treadmill with optic-flow resulted in shorter distance estimates afterwards [Proffitt et al. 2003]. This is in line with other research showing rapid recalibration of human walking using treadmills [Rieser et al. 1995].

Three studies did not provide any feedback in the virtual environment but nevertheless collected distance estimates in reality afterwards. Here, as opposed to when feedback was provided, underestimations were found: Plumert et al. [2005] reported shorter timed imagined walking distance estimates for longer distances in reality after estimating distances in the corresponding virtual environment. Using the same paradigm and environment, Ziemer et al. [2009] found the same trend though not significant. Similarly, Interrante et al. [2008] found a tendency for participants to overestimate distances in a real room immediately after estimating distances in an enlarged virtual replica of it.

In summary, if the virtual environment provides feedback allowing for adaptation, this will in most cases lead to transfer effects to reality. Also making distance estimates in a virtual environment without feedback can influence distance estimates in reality if the virtual environment is a model of the real environment. If there is no closed-loop feedback in the real environment, the transfer effects can persist over at least several minutes [Waller and Richardson 2008]. But this is only the case in the controlled and therefore quite artificial situation of an experiment. In normal life, we always get feedback in our interaction with the physical world. Therefore one could expect that as soon as the artificial experimental situation is over, participants get closed-loop feedback from reality and therefore adapt to the real environment and end the transfer effects. As Waller and Richardson [2008, p.65] report humorously, none of their participants ”walked into the door on the way out of the lab”. Thus, transfer effects are probably not a hazard source. Nevertheless, they might limit the transferability of achievements from virtual to real environments as, for example, with virtual training of ball sports where skill transfer from virtual training to real practice is only found in some cases [Miles et al. 2012].

While transfer effects to reality can be described as taking along virtuality to reality, the opposite - taking reality along to virtuality - hinders a high sense of presence. Presence is defined as a subjective state of consciousness, a participant’s sense of being in the virtual environment [Slater and Usoh 1994]. A number of authors have argued that a higher sense of presence might improve distance perception [e.g., Interrante et al. 2006; Mohler et al. 2008; Phillips et al. 2010; Ries et al. 2009; Steinicke et al. 2010]. So far, there is only indirect evidence to support this hypothesis, on the one hand from studies using avatars and on the other hand from studies using virtual replicas. Providing a virtual body can enhance the participants’ sense of presence [e.g., Bruder et al. 2009; Slater et al. 1994]. Thus, some authors argue that adding an avatar to a virtual environment presented in an HMD might enhance the participants’ sense of presence and thereby improve distance perception [Mohler et al. 2008; Phillips et al. 2010; Ries et al. 2009]. Of all the studies on distance perception with avatars, however, only one measured the participants’ sense of presence [Leyrer et al. 2011]. Unfortunately, they did not report the questionnaire’s results. The accuracy of distance estimates made in a virtual replica of the real environment is also hypothesized to be due to an enhanced sense of presence [Interrante et al. 2006, 2008]. Support of this hypothesis comes from two experiments by Steinicke et al. [2010]. In their first experiment, they found that if participants entered a virtual airplane via a virtual replica of the room, subjects reported a higher sense of presence. In the second experiment, participants entered a virtual city model via the virtual replica of the room resulting in better blind walking distance estimates. Unfortunately, they did not measure the participants' sense of presence in the second experiment. Phillips et al. [2012] assessed the participant's sense of presence using a questionnaire and physiological measures, but did not find any significant correlations to distance estimation accuracy. In summary, so far there is indirect evidence that a low sense of presence might contribute to the underestimation and that the subjective sense of presence might account for some of the individual differences. Further studies are needed to verify this hypothesis.

5.3. Interindividual differences

Many authors mention interindividual differences [e.g., Bingham et al. 2001; Jones et al. 2008; Kenyon et al. 2007b; Luo et al. 2009; Phillips et al. 2010; Ries et al. 2009; Ziemer et al. 2009], though only few discuss possible explanations. Several authors report that they tested for gender differences, but found none [e.g., Creem-Regehr et al. 2005; Interrante et al. 2006; Naceri and Chellali 2012]. Plumert et al. [2005] showed that ten year old children made significant shorter timed imagined walking estimates as compared to twelve year old children and adults. Murgia and Sharkey [2009] on the other hand found no significant influence of age in a distance matching task. Note however that their age range was only 22 to 35 years. Further, Murgia and Sharkey [2009] tested for an influence of individual height and level of experience with CAVEs on distance matching accuracy (level of experience was rated by the participants on a level between 0 -none and 5 -expert). While level of experience reached marginal significance, individual height did not. Armbrüster et al. [2008] tested whether scores in the used stereopsis test can explain some of the individual differences. They found that the higher participants scored in the stereopsis test, the more underestimations they made. Recently, Phillips et al. [2012] correlated the scores of several personality questionnaires that assess personality traits, which are hypothesized to be associated with a higher sense of presence, with distance estimates. They found a significant correlation with the trait absorption indicating that participants who were more open to absorbing and self-altering experiences [Tellegen and Atkinson 1974] underestimated distances to a greater extent.

In summary, gender does not seem to influence distance estimates in virtual environments. The same is true for age, at least when the participants are adults in their twenties or thirties. Age needs to be considered if the participants are children. This is in line with research in real environments showing differing spatial perception in children and older observers [e.g., Bian and Andersen 2012; Harway 1963; Norman et al. 2004]. The level of experience with the used virtual reality hardware system or virtual reality in general might have an influence. Furthermore, vision tests including at least a stereopsis test should be applied because the individual visual abilities could explain at least some of the individual variance. If the above described debate about the influence of personal variables provides more evidence for the hypothesis, personal variables like, for example, intention, stereotype activation, emotion, and desire also have to be considered. Ziemer et al. [2009] recommend large sample sizes to better control for individual differences. But large sample sizes would only allow for group differences to become significant despite the individual differences. It does, however, seem worthwhile to have a closer look at interindividual differences. While those are of growing interest in other fields, they are so far rarely studied in the area of action and perception [Creem-Regehr and Kunz 2010].

6. SUMMARY

For some applications of virtual reality a veridical spatial perception is crucial. Therefore, the question what factors influence egocentric distance perception in virtual en-

Table V. Overview of studies on human factors.

Influence of feedback and practice

First author	**Year**	**Environment**	**Measurement method**	**Hardware**^{a}	**Feedback**	**Effects**^{b}
Altenhoff	2012	Model of a room	Blind reaching Verbal estimates	HMD	Reaching with vision + haptic feedback	Significant N.s.
Interrante	2006	Model of a room	Blind walking	HMD	Haptic feedback	Partial significant
Jones	2011	Model of a hallway	Blind walking	HMD	Peripheral information	Significant
Jones	2012b	Model of a hallway	Blind walking	HMD	Peripheral information	Significant
McManus	2011	Model of a room	Blind walking	HMD	No feedback (mere practice)	Significant
Mohler	2006	Model of a hallway	Verbal estimates Blind walking	HMD	Walking with vision Terminal visual feedback Walking blind +auditory stopp	Significant Significant Significant
Richardson	2005	Textured ground	Blind walking Triangulated blind walking	HMD	Explicit feedback	Significant
Richardson	2007	Textured ground	Blind walking Triangulated blind walking	HMD	Walking with vision +auditory stopp	Significant
Waller	2008	Textured ground	Blind walking	HMD	Walking with vision +auditory stopp Walking blind +auditory stopp Walking around with vision Standing, optic flow human generated Standing, optic flow computer generated	Significant Significant Significant N.s. N.s.
Witmer	1998	Model of a hallway	Blind treadmill walking	BOOM2C	Terminal visual feedback	N.s.

Transfer effects to reality

First author	**Year**	**Environment**	**Measurement method**	**Hardware**^{a}	**Interaction in the virtual environment**	**Transfer to reality**^{c}
Interrante	2006	Model of a room	Blind walking	HMD	Blind walking estimates + haptic feedback	Overestimation
Interrante	2008	Enlarged model of a room	Blind walking	HMD	Blind walking distance estimates	Overestimation
Mohler	2006	Model of a hallway	Verbal estimates Blind walking	HMD	Walking with vision Walking with vision, doupled optic flow	N.s. Underestimation
Plumert	2005	Model of a grassy lawn	Timed imagined walking	3 screens	Timed imagined walking distance estimates	Partly Underest.
Proffitt	2003	Model of a highway	Verbal estimates	HMD	Treadmill with optic-flow Treadmill without optic-flow	Underestimation Overestimation
Waller	2008	Textured ground	Blind walking	HMD	Walking with vision +auditory stopp	Overestimation
Witmer	1998	Model of a hallway	Blind walking	BOOM2C	Blind treadmill walking distance estimates	Underestimation
Ziemer	2009	Model of a grassy lawn	Timed imagined walking	3 screens	Timed imagined walking distance estimates	N.s.

Interindividual differences

First author	**Year**	**Environment**	**Measurement method**	**Hardware**$^{a\ d}$	**Factor**	**Results**^{e}
Armbrüster	2008	Unicoloured surfaces	Verbal estimates	Stereoscopic screen	Stereopsis test score	Significant
Creem-Regehr	2005	Real hallway	Blind walking	—	Gender	N.s.
Interrante	2006	Model of a room	Blind walking	HMD	Gender	N.s.
Murgia	2009	No background or green lattice	Perceptual matching	Four-wall CAVE	Age (22-35) Heigth Level of experience with CAVEs	N.s. N.s. N.s.
Naceri	2012	Dark background	Perceptual matching	Stereoscopic screen	Gender	N.s.
Phillips	2012	Model of a room	Blind walking	HMD	Personality traits	Partial significant
Plumert	2005	Model of a grassy lawn	Timed imagined walking	3 screens	Age (10, 12, Adults)	Significant

[a] HMD stands for head mounted display.

[b] Significant indicates a significant effect of the described type of feedback on distance estimates; N.s. indicates a not significant effect of the described type of feedback on distance estimates.

[c] Overestimation indicates a significant overestimation of distances in a real environment after the described interaction in the virtual environment; Underestimation indicates a significant underestimation of distances in a real environment after the described interaction in the virtual environment; N.s. indicates a not significant change in distance estimates after the described interaction in the virtual environment.

[d] CAVE stands for Cave Automatic Virtual Environment.

[e] Significant indicates a significant influence of the described factor on distance estimates; N.s. indicates a not significant influence of the described factor on distance estimates.

vironments is of great importance. The topic is an interdisciplinary one with contributions mainly from the field of computer graphics and psychology, but other fields as well. This review surveys the growing amount of empirical research on the topic and sorts relevant factors into the four groups measurement methods, technical factors, compositional factors and human factors. In the following section, a summary for every group is provided, conclusions are drawn, and promising areas for future research are outlined.

A variety of measurement methods have been used to make the inner process of perception observable and almost consistently showed an underestimation of egocentric distances. With HMDs blind walking is the most often used and preferable method for distances in action space as is blind reaching in personal space. Given that blind walking is not applicable with other hardware systems, timed imagined walking is suggested instead. In addition to a visually directed action method verbal estimates could be used to detect possibly differing results with this method.

Regarding technical factors, HMD hardware has been shown to account for a certain amount of the distance compression. However, underestimation is not limited to a specific hardware system. Providing motion parallax does not seem to improve distance estimates, while providing binocular disparity does for shorter distances. The conflicting information from accommodation and convergence can influence distance perception and cause visual fatigue. Whether insufficient quality of graphics generates distance underestimation remains an unanswered question. Concerning geometric distortions, a deviating stereo base can influence distance perception at least under some conditions. Further, it can be assumed that incorrect setting of the GFOV and distortions of the angle of declination affect distance perception, while pincushion distortion does not.

Studies on compositional factors show fairly consistently that adding pictorial depth cues improves distance perception. Presenting a virtual replica of the actual room as a virtual environment or as a transitional environment allows a veridical distance perception, which might be due to an enhanced sense of presence. Providing an avatar supposably corrects distance estimates if the user feels the avatar is his or her own body.

The studies reviewed in the human factors section emphasize that feedback including an action component improves distance estimates in the virtual environment and–on the negative side–can alter distance estimates in reality thereafter. Often found interindividual differences might be due to the user's sense of presence, experience with virtual reality, visual ability, or other hitherto untested variables.

In conclusion, to facilitate distance perception as good as possible it is important to provide binocular disparity, use high quality of graphics, carefully adjust the virtual camera settings, display a rich virtual environment containing a regularly structured ground texture, and enhance the user's sense of presence. The latter is probably the most difficult. Because despite a great amount of research there is still much unknown about presence [e.g., Cummings et al. 2012; Schuemie et al. 2001]. This is the first promising field for further research on distance perception in virtual environments as both the effect of an avatar and the effect of replicas and transitional environments are suggested to be mediated by a higher sense of presence. However, empirical evidence for these relations is still missing. Secondly, the problem of graphics quality could be a matter of time and technological development as rendering technologies and hardware performance are still increasing. Applying up to date results of this development might answer the question of whether graphics quality indeed is related to underestimation of distances in virtual environments. A third direction for future research in both virtual and real environments is a closer look at the influence of environmental context. Last but not least, the more applied research question under which conditions the underestimation substantially impairs applications of virtual reality seems worthwhile. To sum up, while a lot of research on egocentric distance perception in virtual environments has been done, much remains to be learned. This review is a first effort to systemize current results and to point out future directions of research. As distance perception is influenced by many factors, additional studies varying and comparing factors from all four groups against each other are called for. The interdisciplinary goal is to provide the knowledge on how to facilitate veridical distance perception in virtual environments and to learn more about the adaptability of human perception.

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