Waiting for the Ultimate Display: Can Decreased Fidelity Positively Influence Perceived Realism?

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Abstract

The first virtual reality (VR) systems have hit the shelves, and 2017 may become the year where VR finally enters the homes of consumers in a big way. By allowing users to perceive and interact in a natural manner, VR offers the promise of realistic experiences of familiar, foreign, and fantastic virtual places and events. However, should we always opt for the highest degree of fidelity when striving to provide users with realistic experiences? In this position paper, we argue that when certain components of fidelity are limited, as they will be in relation to consumer VR, then maximizing the fidelity of other components may be detrimental to the perceived realism of the user. We present three cases supporting this hypothesis, and discuss the potential implications for researchers and developers relying on commercially available VR systems.

Index Terms: H.1.2 [Information Systems]: User/Machine Systems—Human factors; I.3.7 [Computer Graphics]: Three-Dimenshional Graphics and Realism—Virtual Reality;

1 Introduction

A little more than fifty years ago Ivan Sutherland presented his vision of the ultimate display – a room that would be able to manipulate the existence of matter and thereby render objects that not only could be seen and heard but also touched [28]. Three years later Sutherland had developed what he called a head-mounted three-dimensional display [29]. This display could not control the existence of matter, but two small cathode ray tubes offered stereoscopic rendering and a mechanical rig enabled the user to change the virtual view through head movements. Even though Virtual reality (VR) has a long way to go before Sutherland's ultimate display becomes reality, many technological advances have been made since he created one of the earliest head-mounted displays (HMDs), and VR seems closer than ever to becoming a common household item.

One of the defining features that sets VR apart from other media is the ability to elicit a presence response on behalf of the user. Following the view advocated by Slater [22], presence is viewed as the degree to which individuals respond realistically to the virtual environment (VE). Thus, the presence response occurs on multiple levels ranging from unconscious and automatic physiological and behavioral responses to higher level processes involving deliberation and thoughts, including the subjective sensation of "being there" in the VE [21]. Specifically, Slater [22] has argued that this response-as-if-real (i.e., presence [23]) happens as a function of two illusions: the place illusion (PI) and the plausibility illusion (Psi). PI corresponds to the illusion of"being there" in the VE which is contingent upon the range of sensorimotor contingencies supported by the system (i.e., the degree of technological immersion). Psi refers to the illusion that the events happening virtually are indeed happening, and it is influenced by factors such as the extent to which the VE responds to the presence of the user and the general credibility of the scenario [23]. Bowman and McMahan [2] describe that one possible reason for the success of many VR applications is exactly the ability to elicit experiences that greatly resemble the ones faced during real-world interactions. For one, virtual exposure therapy may be used to treat phobias because the experience of a virtual scenario may elicit a genuine fear response. Similarly, VR is of value in relation to military and medical training because the similarity between virtual and real scenarios makes it possible to transfer knowledge and skills from one domain to the other. Finally, Bowman and McMahan [2] describe that to some extent VR also derives its potential as a source of entertainment from the ability to provide users with realistic experiences of places and events that are unlikely or even impossible in real life. However, the new generation of consumer VR systems is still far from offering anything close to the degree of realism envisioned by Sutherland [28].

Two years after Sutherland presented his head-mounted display (HMD), Mori put forth the so-called uncanney valley hypothesis [9]. Particularly, he hypothesized that people will find humanoid robots increasingly empathetic as the robots appearance become more life-like. However, once the degree of likeness reaches a critical point where the robot appears almost, but not perfectly, realistic then human empathy is abruptly replaced by revulsion [10]. Thus, if perfect realism is not attainable there may be a point at which it is disadvantageous to make the humanoid robot increasingly realistic.

In this position paper, we bring to the fore observations made by Nilsson [12], and propose that an analogous, albeit not identical, phenomenon may exist in relation to the relationship between the realism of certain components of VR systems and the degree to which users find the experience realistic; i.e., under certain circumstances, increased realism may cause the user to find the experience less realistic. This is not a problem that is unique to consumer VR, but it is arguably more prevalent since deployment of VR in a domestic setting imposes a number of restrictions that limits the ability to produce near-perfect realism. If high realism of specific components of VR systems indeed is detrimental to perceived realism, it seems crucial to uncover these components since it will help make the experience of everyday virtual reality more realistic.

2 Fidelity Explicated

A VR system that is able to accurately replicate real-world sensory stimuli and interactions is said to have high fidelity [7]. In other words, the level of fidelity is an objective expression of the degree of realism offered by the system. More specifically, McMahan [7] describes that it is possible to break down fidelity into three subcategories: display, interaction, and simulation fidelity. Figure 1 visualizes how the three types of fidelity are connected with the cyclic exchange of information occurring between the user and the system during exposure to VR. Each of the three can be further subdivided into specific fidelity components.

2.1 Display fidelity

Display fidelity is related to the realism of the rendering software and display devices. McMahan [7] defines display fidelity as the objective degree to which the sensory displays can reproduce real-world

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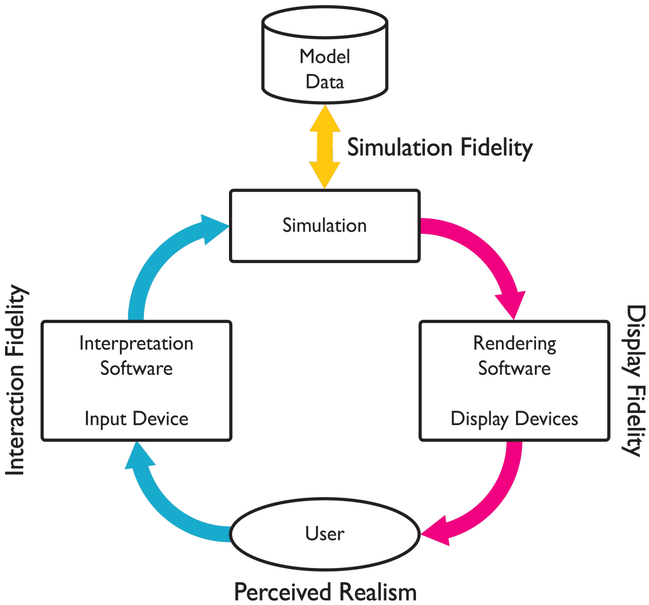

Figure 1: McMahan's [7] version of the user-information loop. Adapted from Nilsson [12].

sensory stimuli. When describing display fidelity, McMahan [7] is primarily focused on visual displays and draws on Bowman and his framework of visual display components [2]. The components of visual display fidelity include, but are not limited to, the refresh rate, frame rate, display resolution, display size, field of regard (FOR), and field of view (FOV) [7]. While it is possible to consider the fidelity of a unimodal display (e.g., a HMD), it should be stressed that VR systems with high display fidelity are able to render multisensory stimuli in a manner that faithfully reproduces their real-world counterparts.

The display fidelity of commercial VR systems is necessarily limited. Premium systems, such as the Oculus Rift and HTC Vive, provide audiovisually impressive experiences. However, they do not fully cover the visual field of the user, high-resolution, stereoscopic rendering of photorealistic imagery at high frame rates remain an obstacle, and real-time synthesis of spatialized audio is seldom the norm. Moreover, a system providing universal haptic feedback is unlikely to become commercially available within a foreseeable future. At best, current systems allow users to interact with virtual objects through controllers that provide limited vibtrotactile feedback.

2.2 Interaction fidelity

McMahan [7] describes interaction fidelity as the objective degree to which the physical actions of the user are equivalent when performing the same task in the VE and the real world. In particular, he has proposed that interaction fidelity can be decomposed into the three general components: biomechanical symmetry, control symmetry, and system appropriateness (see Table 1 for a summary).

The controllers compatible with the HTC Vive and Oculus Rift offer a reasonably high degree of interaction fidelity as long as the user performs hand-based interaction with virtual objects that resemble the shape and weight of the controllers. However, as soon as the user interacts with an object that differs noticeably in terms of shape or weight, biomechanical symmetry will be limited. Moreover, these systems allow the user to walk naturally within a limited tracking space. Thus, interaction fidelity is high with respect to walking, as long as the user does not move beyond the tracked space.

Table 1: Summary of McMahan's [7] delination of interaction fidelity, as presented by Nilsson [12].

Biomechanical symmetry: The degree of symmetry between actions performed during real and virtual tasks may be described by the objective extent to which the physical movements correspond across the two tasks. The movement may be described in terms of: - *Kinematic symmetry:* The degree to which the real-body motions are reproduced. - *Kinetic symmetry:* The degree to which internal and external forces are reproduced. - *Anthropometric symmetry:* The degree to which the body segments used to perform the virtual action corresponds with the ones used when performing the real action.
Control symmetry: Control symmetry describes the objective extent to which an interaction technique offers the same amount of control as when the task is performed in the real world. McMahan considers the correspondence between three aspects of control across real and virtual actions: - *Dimensional symmetry:* The degree to which the interaction reproduces control in the same dimensions (e.g., position and orientation). - *Transfer function symmetry:* The degree to which the translation of input data into output effects is reproduced. - *Termination symmetry:* The degree to which a virtual action is terminated as it would be in the real world.
System appropriateness: According to McMahan, it is possible to characterize a system based on how appropriate it is for implementing certain types of interaction based on four factors: - *Input accuracy:* The degree to which the registered values represent the "true" values. - *Input precision:* The degree to which the values will be the same across multiple readings under static conditions. - *Latency:* The amount of temporal delay between the users action and system response. - *Form factor:* The shape and size of the input device.

2.3 Simulation fidelity

Finally, simulation fidelity refers to the objective degree to which the system can reproduce real-world physics and characteristics [7]. Thus, simulation fidelity is associated with the realism of the models forming the basis for the generation of the VE (e.g., geometric, lighting, or physical models).

McMahan [7] does not describe simulation fidelity in great details, but it arguably also includes a variety of other characteristics such as the behavior of simulated virtual characters. Thus, the simulation fidelity of consumer VR systems is constrained by the limited processing power of affordable computers and limited ability to accurately simulate natural phenomena, including the behavior of humans and other sentient beings.

3 When Higher Fidelity is Not Enough

The concepts display, interaction and simulation fidelity are useful when we wish provide an objective account of how well displays, tracking systems, and algorithms approximate reality. However, exactly because fidelity amounts to an objective description of a system, it may fail to capture the degree of perceived realism; that is, the extent to which user finds the VE and the interactions taking place within it mistakable for the real thing. Figure 1 illustrates the user-information loop and the relationship between perceived realism and display, interaction, and simulation fidelity.

For good reasons, this claim may seem counter intuitive at first glance. A VR system with perfect fidelity would arguably be indistinguishable from real life. Thus, a decrease in either display, interaction or simulation fidelity is unlikely to go by unnoticed, exactly because the system is able to perfectly mimic reality in all other regards. Moreover, it generally seems safe to assume that a large increase in fidelity will be followed by an increase in perceived realism. Indeed, this seems likely to be the case. For example, a scenario requiring the user to navigate a VE on foot, should be perceived as more realistic if the navigation is accomplished by physically walking (high interaction fidelity), rather than using a game controller (low interaction fidelity). A recent study by Nabiyouni et al. [11] lends support to this claim since it showed that participants found walking in the Virtusphere (a human-sized hamster ball) significantly less natural than real walking but more natural than using a gamepad.

However, current VR systems in general, and commercially available systems in particular, do not have perfect fidelity, and users are likely to encounter situations where the system cannot faithfully reproduce real-world sensory stimuli, interactions, and behaviors. It is exactly when certain components of display, interaction of simulation fidelity are limited, that it may counterproductive to opt for the highest possible level of fidelity in regards to other components. That is, during certain circumstances increased fidelity may be at odds with perceived realism. Three examples, identified Nilsson [12], lend themselves well to illustrate this point:

3.1 Case I: Natural Perspective Projections

Steinicke et al. [26] describe that in order to provide the user with an undistorted view of the VE, the geometric FOV should be configured so that it matches the display FOV of the HMD. The geometric FOV and the display FOV refer to the horizontal and vertical angles subtended by the virtual viewing volume and the display, respectively. If the gemoetric FOV is larger than the display FOV more geometry is forced into the projected image and the VE will appear minified. Conversely, if the geometric FOV is smaller than the display FOV less geometry will be fitted into the displayed image and the VE will appear magnified. Hence, the two types of distortion has been referred to as minification and magnification [26]. Somewhat surprisingly, work by Steinicke et al. [26] suggests that individuals wearing a HMD might not find the undistorted view of the VE to accurately represent their view of an identical real environment. Particularly, the participants found some degree of minification to be more realistic than the undistorted view. Also, the results indicated that the amount of minification required for perceptually realistic viewing experiences decreased as the display FOV became large. Minification may be regarded as a reduction in fidelity because the projected image, objectively speaking, does not replicate the equivalent view of the real world. Thus, it would seem that when relying on a HMD that is less than perfect in regards to one component of display fidelity (a display FOV that does not fully cover the user's visual field), then it may be beneficial to reduce the fidelity of another component so as to increase perceived realism (introducing a distortion in the form of minifiction).

3.2 Case II: Visual Motion Perception

While VEs can be virtually infinite in size, the physical space available for interaction will to be limited in size. This is particularly likely in regards to VR deployed in a domestic setting. Numerous locomotion techniques have been developed with the aim of giving users a natural walking experience while keeping them within confined physical space (e.g., [4, 8, 20]). However, if the task at hand simply involves walking along a straight path a linear treadmill is a viable option. Intuitively one would assume that the user's virtual speed should match the speed at which the treadmill belt is moving. However, it has been demonstrated that walkers tend to underestimate visually presented speeds that are matched with the speed of the treadmill; i.e., they find the speed of movement through the VE too slow [1,6,18]. Thus, it may be necessary to exaggerate the visual speed in order to preserve perceived realism. However, presenting users with unrealistically fast walking speeds arguably reduces interaction fidelity. Specifically, transfer function symmetry would be reduced because the user's input is not translated into a realistic output (i.e., the user's gait does not result in a realistic speed). Notably, it has been shown that the size of the display FOV influences how much the virtual speed should be exaggerated in order for the user to find it realistic. That is, walkers tend to favor higher virtual speeds when a smaller portion of their visual field is occupied by the VE (i.e., the display FOV is smaller) [15]. Thus, again it would appear that when display fidelity is imperfect, it may be necessary to reduce another component of fidelity to increase perceived realism. Interestingly, this perceptual distortion may also be affected by the limited interaction fidelity inherent to treadmill-mediated walking. Because this form of locomotion does not involve any notable physical translation, no vestibular motion cues are generated. Thus, the need for decreasing transfer function symmetry by exaggerating the virtual speeds may also be brought about by limitations to kinetic symmetry (another component of interaction fidelity). Virtual speeds may also be underestimated during walking-in-place (WIP) locomotion [15]) where the user generates virtual movement by performing a stepping-like gesture serving as a proxy for real steps.

3.3 Case III: Gestural Input for In-Place locomotion

The third example of a case where a decrease in fidelity may produce higher perceptual realism, relates to the gestural input for WIP locomotion. WIP locomotion constitute a promising approach to facilitating relatively natural walking experiences in relation of consumer VR since it can be used in a room of limited size and has already been implemented using commercially available hardware such as Microsoft's Kinect [27], Nintendo's Wii Balance Board [30], and the inertial sensors of Samsung's Gear VR [17]. A primary advantage of WIP locomotion is that the steps in place generate proprioceptive feedback reminicient of the one produced during real walking [24]. Most existing WIP techniques take the same gesture as input. The user alternately lifts each foot off the ground as if marching on the spot or climbing a flight of stairs. Even though WIP locomotion offers some degree of interaction fidelity, the biomecanics of stepping in place differs considerably from the real walking. Most notably, the walker lifts each leg vertically, rather than swinging them. Studies have shown that gestural input involving more subtle leg movements (tapping one's heels against ground) or gestures devoid of explicit leg movement (swinging one's arms) may serve as a better proxy for real walking with respect to perceived exertion and be comparably to the traditional gesture in terms of perceived naturalness [13, 14]. In both cases kinematic symmetry is reduced since the user no longer breaks contact with the ground. However, kinetic symmetry is arguably increased since the energy expenditure better resembles real walking. Thus, it would seem that it sometimes even may be advisable to reduce one sub-component of interaction fidelity, if it entails an increase in another.

4 Perceptually Informed Degradation of Fidelity

The three cases outlined in the previous section lend some support for the hypothesis that the relationship between components of fidelity and perceived realism at times may be contrary to common sense. When certain components of fidelity are imperfect, then high fidelity with respect to other components may be detrimental to perceived realism. Consequently, we suspect that developers and researchers relying consumer VR systems with inherently imperfect fidelity at times may benefit from strategically reducing the fidelity of certain components. Because perceived realism ultimately is a subjective response to the user-information loop (Figure 1), we argue that the decision of what components to reduce, if any, in many cases should be perceptually informed. In particular, we propose that when limitations to a given component of fidelity reduces or distorts perceptual information, then sometimes it may be possible to compensate by adjusting another component of fidelity–even if the adjustment on the surface constitutes decrease in the fidelity of the second component.

Using the cases as examples, when faced with a limited display FOV the user is obviously deprived of visual information in the periphery. While increasing the geometric FOV introduces a distortion (i.e., minification), the participants in the study by Steinicke et al.'s [26] may have felt that the distorted view of the VE was truer to the one experienced during perception of the real world because it made objects, normally captured by peripheral vision, visible.

Similarly, because peripheral vision plays a role in motion perception [19], the underestimation of visually presented speeds, described in relation to the second case, is also to be expected when relying on a HMD with a limited display FOV. However, it is possible to compensate for the missing peripheral motion cues by exaggerating the virtual speed. Notably, some evidence suggests that minification also will decrease the underestimation of virtual walking speeds [16]. Moreover, individuals walking on a treadmill are deprived of vestibular motion cues which may explain why they find higher virtual speeds realistic compared to individuals who are physically walking through the VE (as exemplified by the detection thresholds for redirected walking [25]).

Finally, the case of alternative gestural input for in-place locomotion suggests that the marching-like gesture, that on the surface seems most appropriate due its resemblance with the real gait cycle, might not be optimal because it is perceived as too physically straining. The two alternative gestures (heel tapping and arm swinging) mimics the kinematics of real walking to a lesser degree but because it requires less effort, the trade-off appears to be worthwhile.

5 Discussion

In this position paper we have presented three claims: (1) When the fidelity of a system is limited, then the relationship between fidelity and perceived realism need not conform to the intuition that increased fidelity always produces more realistic experiences. (2) As a consequence we hypothesized that researchers and developers at time may be able to increase perceived realism by deliberately reducing the realism of specific components of fidelity. (3) A possible explanation is is that limitations to a given component of fidelity will reduce the quality of perceptual information, and it may be possible to compensate by reducing the fidelity of other components, thus producing higher perceptual realism.

The studies forming the basis for the three cases outlined in section 3 lend some support to the first and the second claim. However, it is worth questioning whether a decrease in the realism of a single component of fidelity, in order to make up for the limitations of another, constitutes a decrease in overall fidelity or not. To exemplify, the minfied view of the VE deemed the most natural by the participants in the study by Steinicke et al. [26] need not qualify as a general decrease in display fidelity. As noted by Nilsson [12], the minification simultaneously represents decreased fidelity of the FOV mapping and an increased fidelity of the FOV coverage. Regardless of whether we can say that the overall display fidelity is reduced or not, the hypothesis arguably still stands. That is, a decrease in fidelity of an individual component may elicit higher perceived realism. While the three cases do lend some credence to the first two claims, they constitute isolated instances where decreased fidelity of single components appear to increase perceptual realism, and do by no means confirm that one, when faced with an imperfect VR system, always should reduce the realism of components of fidelity.

Inherent to the third claim is the proposal that knowledge of human perception provides us with a good starting point for determining when decreased fidelity may be beneficial (e.g., bottom-up processes related to motion perception help explain why it is meaningful to exaggerate virtual walking speeds or the geometric FOV when the display FOV does not cover the full visual field). However, bottom-up processes might not always provide the best point of departure. This seems specifically true, in regards to certain parts of the relationship between simulation fidelity and perceived realism (e.g., higher-level cognitive processes are likely to play a role when judging the realism of virtual character's behavior).

In the current paper we have not explicitly addressed how perceived realism is related to Slater's [22] two orthogonal components of presence, PI and Psi. Thus, it is worth stressing that perceived realism and presence appear to be inherently connected. Slater [22] describes presence as the degree to which individuals respond realistically to VEs, and in this paper we described perceived realism as the extent to which user finds the VE and the interactions taking place within it mistakable for the real thing. Thus, perceived realism may be viewed as part of the perceptual component of this multilevel response-as-if-real.

As such this position paper does not (and did not seek to) provide an exhaustive account of the available evidence nor provide a fully-fledged theory of nature of the relationship between fidelity and perceived realism. Future work should seek to more systematically identify and study instances where increased fidelity may be at odds with perceptual realism and possibly presence. At least two different, yet complementary, approaches seem relevant. One or more critical reviews of the literature may help identifying additional cases (i.e., an exhaustive search of relevant work based on reproducible criteria [3]), and empirical studies based psychophysical methods may provide empirical evidence supporting or contradicting the proposed hypotheses (e.g., the method of adjustment may prove useful for initial probing [5]).

6 Conclusion

Laboring under the assumption that perceived realism can be increased by strategically reducing components of fidelity, this may enable developers and researchers relying on consumer VR systems to provide users with more realistic experiences through perceptually (and cognitively) informed predictions about how to compensate for the technological limitations inherent to such systems. Future developments will inevitably bring us closer to realizing Sutherland's vision of the ultimate display. However, while we wait for the ultimate display to become reality, it seems worthwhile to explore other approaches to providing consumers and professionals with more realistic experiences. Thus, it seems meaningful for future work to address the question: can decreased fidelity positively influence perceived realism?

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