Going With the Flow: Modifying Self-Motion Perception with Computer-Mediated Optic Flow

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ABSTRACT

One major benefit of wearable computers is that users can naturally move and explore computer-mediated realities. However, researchers often observe that users' space and motion perception severely differ in such environments compared to the real world, an effect that is often attributed to slight discrepancies in sensory cues, for instance, caused by tracking inaccuracy or system latency. This is particularly true for virtual reality (VR), but such conflicts are also inherent to augmented reality (AR) technologies. Although, head-worn displays will become more and more available soon, the effects on motion perception have rarely been studied, and techniques to modify self-motion in AR environments have not been leveraged so far.

In this paper we introduce the concept of *computer-mediated optic flow*, and analyze its effects on self-motion perception in AR environments. First, we introduce different techniques to modify optic flow patterns and velocity. We present a psychophysical experiment which reveals differences in self-motion perception with a video see-through head-worn display compared to the real-world viewing condition. We show that computer-mediated optic flow has the potential to make a user perceive self-motion as faster or slower than it actually is, and we discuss its potential for future AR setups.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems—Artificial, augmented, and virtual realities; I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1 INTRODUCTION

Computer-mediated reality refers to the ability to manipulate one's perception of the real world through the use of wearable computers such as head-worn displays or hand-held devices. Applications include the visual augmentation of the real world with virtual objects, but can also encompass the visual "subtraction" of certain objects or information from the real world, for instance, to provide an alternative perspective [1]. As a result, the view of the real world can be modified in two ways, i. e., *diminished* as well as *augmented*. Although the technology has reached a level where effective computer-mediated realities can be designed, researchers and practitioners are still attempting to solve many fundamental problems. For example, it is an often observed phenomenon that users perceive a computer-mediated reality with scene and depth distortions, which can potentially lead to poor task performance [18, 23]. While most of the previous work in augmented reality (AR) research in this context was focussed on registration, illumination and depth problems, the perception of motion was ignored for a long time [18]. With the rapid advent of applications based on wearable computers such as cell phones or head-worn displays, it can be foreseen that users will soon be able to explore computer-mediated realities, for example, by walking or driving around. Hence, it is crucial that we gain a better understanding of the perception of motion in computer-mediated realities.

It is still an open research question whether and how the perception of self-motion is affected in AR environments, i. e., if self-motion perception is changed by optical or video see-through equipment. In contrast, significant effort has been undertaken in virtual reality (VR) to determine perceptual limitations and misperception during self-motions in immersive display environments [43, 46]. In particular, Razzaque et al. [33] conceptually proposed and Steinicke et al. [40] experimentally determined points of subjective equality as well as detection thresholds for a variety of walking motions in immersive head-mounted display (HMD) environments. The results revealed significant misperception of walked distances and head turn angles, which greatly limit the applicability of immersive virtual environments (IVEs) for exploration tasks, e. g., in the field of construction or architecture, in which an accurate spatial impression of virtual models is essential [14].

However, the observation that self-motion perception in IVEs is limited and biased has also introduced a range of novel interface characteristics that become possible by exploiting perceptual limitations. In particular, the finding that users are often not able to consciously detect slight discrepancies between self-motion in the real world and in virtual scenes has stimulated multiple research directions that imperceptibly guide users on paths in the real world that differ from the visually perceived paths [33]. A growing number of applications are based on exploiting undetectable subliminal sensory manipulations, enabling new research directions, such as the natural interaction with impossible spaces [44].

For augmented reality (AR) environments, such approaches based on exploiting limitations of self-motion perception have not been studied so far. One reason could be that it is not trivial to introduce a discrepancy between actual and visually perceived position or orientation in AR. However, research on visual illusions in IVEs based on optic flow fields recently suggested that it may be possible to change a user's self-motion perception even with AR displays [5]. The illusions were based on the direct stimulation of retinal motion detectors using the transparent overlay of rendered scenes with three-dimensional virtual flow fields [11], contrast inversion or change blindness illusions [39], or time-varying displacements of object contours [9]. Until now, the potential of changing self-motion perception in AR via integration of actual and apparent optic flow motion sensations has not been considered.

The paper is structured as follows. Section 2 provides background information on self-motion and optic flow. Section 3 presents three techniques to manipulate optic flow fields in AR. Section 4 describes the psychophysical experiment that we conducted to evaluate the techniques. Section 5 concludes the paper.

2 BACKGROUND

In this section we give an overview of self-motion perception, optic flow, and illusory transformations in optic flow patterns.

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2.1 Self-Motion Perception

The perception of self-motion speed, direction and path of travel is based on the combination and integration of various cues provided by the sensory systems [2]. When moving in the real world, humans receive vestibular information about linear and angular accelerations of the head [33], as well as proprioceptive and kinesthetic information about the locomotor state of the body [43]. The information from the body senses is supplemented by auditive and visual sensory information about the movement of the observer relative to the environment. Visual information consisting of landmarks and optic flow [20] has often been found to *dominate* self-motion perception [3, 5], suggesting that visual stimulation often provides the most reliable cues about travel distance and direction. This observation is often exploited in IVEs, in which users experience virtual self-motion via visual displays, while cues from the body senses in the real world often indicate limited or no self-motion at all [38].

However, even if a user's head movements are mapped veridically to a virtual camera in IVEs, the different sensory cues often do not agree as in the real world, which results in large differences in spatial and self-motion perception [40, 43]. Various hard- and software factors have been elucidated that can cause misperception in IVEs. However, the major contributing factors remain unknown [14]. Distance and size misperception effects in AR environments are often found to occur at a much lower degree than in IVEs [17]. So far, limited information exists on how technical or cognitive issues in AR environments affect self-motion perception.

2.2 Optic Flow

The pattern of light rays that reach an observer's eye after being structured by surfaces and objects in the world can be seen as an *optic array*. When an observer moves in the world the motion that is produced in this array is called optic flow [10]. For example, forward movement produces optic flow radiating out from the point the observer is heading towards, which is visually observable as the focus of expansion (see Figure 1), whereas backward movements create a focus of contraction in the optic array. Especially in peripheral regions of the visual field, the sensitivity to self-motion information from optic flow is very high [5, 31]. When incoming signals from the various senses are inconsistent, optic flow can dominate self-motion perception [35]. For example, when a neighboring train starts to move while sitting in a stationary train, a sensation of self-motion is caused although mechanical forces on the body do not change. This phenomenon is called *vection* [3]. The influence of optic flow on self-motion perception has been shown by many studies. Lee and Lishman [22] used a "swinging room" where the walls could be moved backwards or forwards unnoticed by the subject. When movement of the walls caused optic flow that would be produced when swaying towards the wall, subjects swayed or fell backward. Pailhous et al. [30] varied optic flow velocity while subjects were instructed to maintain a constant walking speed. They observed modulations in stride length and cadence. Rieser et al. [36] investigated aftereffects of discrepancies between optic flow velocity and walking speed. After walking for a while, subjects had to walk blind-folded to a distant target. The group that had previously walked faster than specified by the optic flow overshot the target while the other group undershot it.

2.3 Motion Illusions

The visual system uses all motion information available in the visual field to build a percept of self-motion. When specific motion patterns are added to an optic flow field, illusory percepts can arise even if the basic motion pattern remains unchanged. Duffy and Wurtz [7] presented an outward radial optic flow field that was overlapped by unidirectional horizontal motion. Although subjects perceived two different motion patterns, they reported a change in their self-motion percept. The focus of expansion appeared to be shifted in the direction of the horizontal motion. A simple vector averaging of the flow fields could not account for the illusion because it predicts a shift of the focus of expansion in the opposite direction. The illusion has rather been explained by compensatory heading detection mechanisms that shift the perceived heading against the rotation of the observer [21]. Bruder et al. [5] manipulated peripheral optic flow in an IVE by overlaid three-dimensional motion, masked phases of camera offsets and time-varying displacements of object contours. After walking a few meters in the virtual scene, subjects had to decide whether their virtual movement was smaller or larger than the physical movement. In all conditions manipulations affected subjects' percepts of self-motion. However, in the overlaid condition, only one of three manipulations had significant impact on subjects' judgments, namely motion of textures fitted to the scene. Simple particle flow and moving sinus gratings had no significant effect, probably because the visual system interpreted them as external motion in the scene, rather than self-motion. Changing global image properties can also lead to illusory percepts of self-motion derived from optic flow. In simulated driving environments it has been found that a reduction of luminance increases perceived speed while a reduction of contrast decreases it [32, 37].

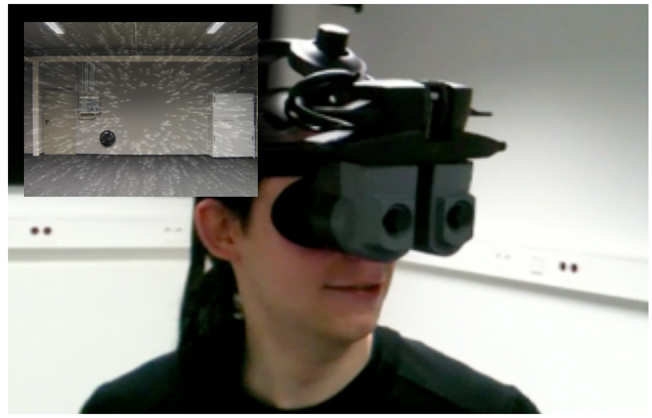


Figure 1: Photo of a user wearing a tracked NVIS nVisor MH-60V video see-through HMD. The inset shows an illustration of the resulting expansional optic flow field during forward movements.

3 COMPUTER-MEDIATED OPTIC FLOW

In this section we describe how visual self-motion feedback can be changed with video see-through displays using techniques based on optic flow manipulations. In the following, we assume that a user is wearing a video see-through HMD which is tracked in an environment that supports natural locomotion. For each frame the change in position $\vec{p} \in \mathbb{R}^3$ and orientation with Euler angles $\vec{o} \in \mathbb{R}^3$ from the previous tracked state to the current state is measured. The differences in position and orientation divided by the elapsed time $\Delta t \in \mathbb{R}$ between rendering frames can be used to compute and manipulate the velocity of optic flow fields.

Three types of optic flow manipulations can be distinguished: those that are based on temporal transformations, those that make use of screen space transformations, and those that introduce pixel motion to increase, decrease or redirect optic flow patterns. In the following sections, we focus on translational self-motions and present different approaches to introduce optic flow patterns that differ from the visual fields naturally experienced when moving in AR environments. We discuss how these can be parametrized and steered with gains $g_v \in \mathbb{R}$ denoting scale factors of the visual self-motion velocity. Using this parametrization, gains $g_v > 1$ result in an increased visual self-motion velocity, whereas gains $g_v < 1$ decrease the visual velocity.

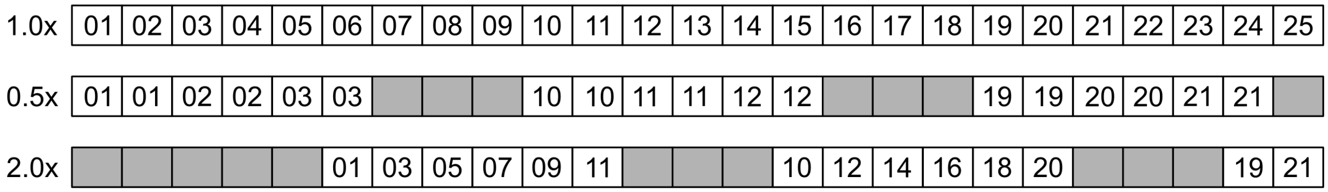


Figure 2: Illustration of different temporal transformations: The top row shows camera images captured at each frame and displayed to the user on the video see-through display, which results in a natural visual velocity. The center row illustrates temporal expansion by displaying each camera image for twice its natural time span resulting in half the visual velocity. The bottom row illustrates temporal compression by skipping each second camera image resulting in twice the visual velocity. The blank screens denote inter-stimulus intervals.

3.1 Temporal Transformations

Video see-through HMDs are based on the principle that images are captured by built-in cameras at the approximate positions of the user's eyes, processed, and presented on visual displays to the eyes of the user. Usually, for each rendering frame the most current camera images are displayed to minimize latency between movements in the real world and their feedback via the AR display (illustrated in Figure 2(top)). However, motion feedback with video see-through displays can be changed by introducing offsets between subsequently captured camera images. Constant offsets, e. g., presenting the *n*th previously captured image to the user, correlate to changing the latency of the AR system. In contrast, using dynamic offsets, such as skipping every second frame or displaying each captured camera image for two frames on the HMD, results in accumulating temporal offsets and can disrupt the natural perceived temporal continuum (see Figure 2). While such temporal compressions or expansions provide the means to change the perception self-motion velocity, the inherent accumulation of latency reduces their applicability over time frames of more than a few hundred milliseconds.

A recently proposed solution to keeping accumulating offsets in check has been observed by Bruder et al. [5] and originates in the field of *change blindness* illusions [34, 39]. Change blindness denotes the phenomenon that an observer presented with a visual scene may fail to detect a significant change in the scene in case of a brief visual disruption, in particular, if the visual disruption is long enough to clear the retinal afterimage or provoke contrast inversion in the afterimage [27]. Rensink et al. [34] observed that when changes to the scene are synchronized with measured blinks or saccades of an observer's eyes, e. g., exploiting *saccadic suppression*, scene changes can be introduced roughly every 250ms (assuming about 4 saccades and 0.2 blinks per second for a healthy observer [6]). Additionally, Rensink et al. [34] showed that blanking out the screen for 60-100ms is well suited to introduce a controllable visual disruption that can be used to stimulate and study change blindness in a visual scene.

Figure 2(bottom) illustrates in which order captured camera images can be displayed to an observer so that the resulting visual velocity is always twice ($g_v = 2$) as fast as using a veridical mapping. The blank display frames denote how change blindness can be used to hide a backward jump in time from the observer, in particular, without stimulating retinal motion detectors during reverse motion. Figure 2(center) provides an example for reducing visual velocity by 50% ($g_v = 0.5$), in which the blank frames conceal a forward jump in time. The maximal latency introduced by the two examples is defined by how often visual disruptions naturally occur or can be introduced with blank screens, i. e., how often change blindness can be exploited. While the temporal scale factors shown in Figure 2 are easy to implement, variable visual velocities can be introduced by blending or morphing intermediate images between two camera frames (e. g., based on Mahajan et al. [26]).

3.2 Screen Space Transformations

It is quite common with video see-through HMDs that the built-in cameras have a slightly larger field of view than provided by the display optics. As a result, the visual angles have to be calibrated to provide a matching view of the real world as without the AR HMD. In the following, we denote the view angles of the camera images as *camera field of view* (CFOV), and that of the HMD as *display field of view* (DFOV). If the CFOV matches the DFOV (i. e., CFOV=DFOV), the viewport is mapped from the camera space onto the physical display in such a way that users perceive a "correct" perspective of the real world (assuming that we neglect other distortions of the camera or HMD such as pincushion distortion [19]). In case of CFOV<DFOV, the view of the real world appears magnified on the display, such as with a telephoto lens, because of the requirement for the camera image to fill a larger subtended angle of the HMD optics [19]. For CFOV>DFOV, the view of the real world is minified and compressed in a smaller visual field such as with a wide-angle lens [19]. Mini- and magnification change several visual cues that provide distance information. In particular, the changed retinal size makes familiar objects appear closer or farther away [25], and binocular convergence indicates a shift in distance [4].

Controllable *mini-* and *magnification* can be implemented for a fixed CFOV and DFOV as follows. With gains of $g_F \leq 1$ the used image region of the total CFOV can be changed as $g_F \cdot$ CFOV. Steinicke et al. [42] proposed the following equation to compute the amount of mini- or magnification of the view:

$$m = \frac{\tan\left((g_F \cdot \mathrm{CFOV}) \cdot 0.5\right)}{\tan(\mathrm{DFOV} \cdot 0.5)} \tag{1}$$

for vertical fields of view with $m < 1$ denoting view magnification ($g_F \cdot \mathrm{CFOV} > \mathrm{DFOV}$), and $m > 1$ denoting view minification ($g_F \cdot \mathrm{CFOV} < \mathrm{DFOV}$). As described by Bruder et al. [4], mini- or magnification cause visual distance cues to be changed:

$$\widehat{D} = D \cdot m \tag{2}$$

with D the actual distance to a scene object and $\widehat{D}$ the resulting object distance along the view axis after mini- or magnification.

Figure 3 shows an example in which the top row corresponds to the actual forward motion of an observer, and the bottom row shows effects of introducing additional magnification each frame. The AR view shown in the bottom row indicates an increased visual velocity, and makes use of change blindness inter-stimulus intervals (see Section 3.1) to revert the accumulated magnification in the view. While the results differ in geometric distortions, previous studies have shown that users tolerate a certain deviation in perspective cues with HMDs, and often are not even able to detect a discrepancy [41, 42]. Depending on the CFOV of the built-in cameras of the AR HMD, a similar effect can be achieved for minification.

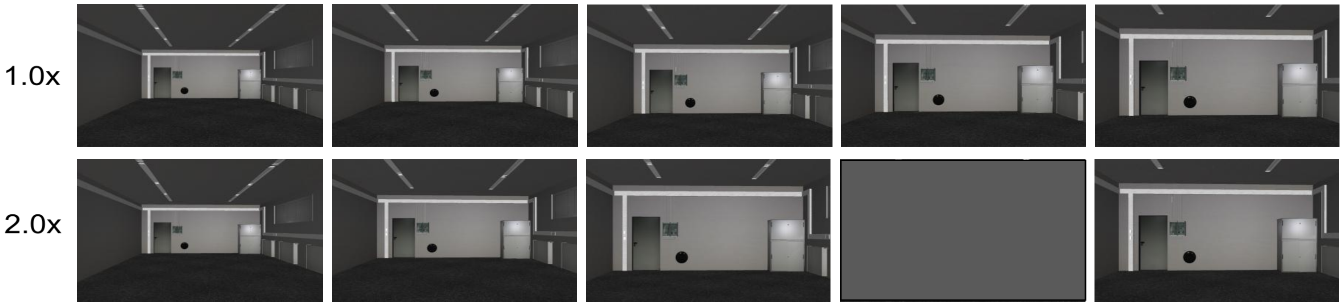


Figure 3: Illustration of screen space transformations: The top row shows camera images captured while the observer is moving forward. The bottom row shows an increased visual velocity with magnification and change blindness. The blank screen denotes an inter-stimulus interval.

3.3 Pixel Motion Transformations

While moving with a video see-through HMD, light intensities move over the visual field, which stimulate retinal motion detectors. Although the perceptual system uses different local and global approaches to filter out noise in retinal flow [13, 27], different approaches to manipulate visual information have been proposed that have the potential to subliminally change percepts of visual velocity (see Section 2). In order to introduce a flow field to the periphery of the AR view on a video see-through HMD, we implemented a GLSL shader to dynamically move pixels with or against the tracked self-motion direction using an approximate model of optic flow directions on the display surface. Scaled 2D optic flow direction vectors can be extracted from subsequent camera images (cf. [47]). With this approach, the final color of fragments is computed using time-varied weights:

$$\sum_{i=0}^{n-1} texture2D(cam, c + d \cdot (i+1)) \cdot \frac{n-i}{n} \cdot \left(\left(t + \frac{i}{n} \right) \% \frac{1}{2} \right) \quad (3)$$

along the 2D optic flow direction vector $d \in \mathbb{R}^2$ with pixel coordinate $c \in \mathbb{N}^2$, scaled frame time $t \in [0,1]$, and $n \in \mathbb{N}$ (e. g., $n = 30$). Since the direction vectors d can be determined for each pixel using optic flow estimates between the current and last camera image, and their non-normalized length encodes the user's movement velocity, the pixel velocity over the periphery can be changed by $t = t + \alpha \cdot \Delta t$, with a speed factor $\alpha \in \mathbb{R}$.

Using this shader, selected pixels (e. g., only those in the periphery [5]) can be moved with or against the user's self-motion direction, thus changing the velocity of the retinal flow field (see Figure 4). The looped filter ensures that the peripheral flow field is perceived as continuous motion.

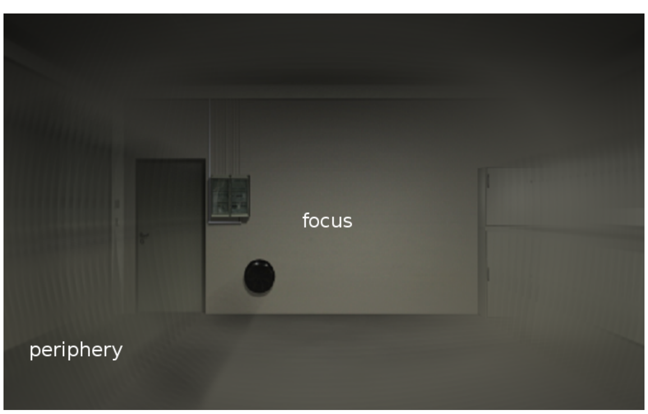


Figure 4: Example of pixel motion transformation with a faster or slower flow field introduced in the periphery of the observer's eyes.

4 Experiment

In this section we describe an experiment that we conducted to evaluate self-motion estimation in an AR environment based on a video see-through HMD. We analyze whether it is possible to change self-motion judgments with the visual augmentation techniques presented in Section 3. Although literature suggests that visual self-motion cues can dominate extraretinal cues [3, 5], it is unclear whether the proposed techniques can actually affect self-motion judgments. Studies investigating the effects of self-motion manipulations often used an adaptation procedure and measured blind-walking performance in pre- and post-tests [8, 29, 36]. Here we used a condensed version of this method assuming that our techniques will have immediate effects on self-motion judgments. A single trial consisted of a stimulus phase with vision and an estimation phase without vision. We compared subjects' blind walking distances towards targets directly after a stimulus phase with visual self-motion information. We varied the visual self-motion velocity by applying the augmentation algorithms with different parameters $g_v \in \mathbb{R}$ in the stimulus phase. During the estimation phase the perceived self-motion velocity of the stimulus phase should influence the distance updating process. When the computer-mediated optic flow changes a subject's perceived self-motion velocity, the subject may walk farther or shorter than the unmediated target distance.

4.1 Experimental Design

We performed the experiment in a 12m×7m darkened laboratory room. As illustrated in Figure 1, subjects wore a professional binocular NVIS nVisor MH60-V video see-through AR HMD for the stimulus presentation, which provides a resolution of 1280×1024 pixels with an update rate of 60Hz and a 60° diagonal field of view (modulo pincushion distortion [19]). The integrated VideoVision stereo cameras provide a resolution of 640×480 with an update rate of 60Hz and a slightly larger field of view of approximately 78°, which we matched to the HMD. We measured an end-to-end latency of approximately 110ms with the video see-through HMD by evaluating the response time of photodiodes using A/D-converters. We tracked the HMD within the laboratory with a WorldViz Precision Position Tracking PPT-X4 active optical tracking system at an update rate of 60Hz. For rendering, system control and logging we used an Intel computer with 3.4GHz Core i7 processor, 16GB of main memory and Nvidia GeForce GTX 680 graphics card. The stimuli were introduced to the AR view using OpenCV, OpenGL, and GLSL. Subjects judged their perceived self-motions via button presses on a Nintendo Wii remote controller.

4.2 Participants

10 male and 10 female (age 20-44, avg: 27.7) subjects participated in the study. All subjects were students or members of the departments of computer science or psychology. All subjects had normal or corrected to normal vision; 6 wore glasses and 2 contact lenses

Figure 5: Experiment setup: subject walking in the direction of a target displayed at eye height for a distance indicated by the center of two vertical poles.

during the experiment. None of the subjects reported known eye disorders, such as anisometropia, strong eye dominance, color or stereo blindness, and none of the subjects reported disorders of the proprioceptive-vestibular systems. 9 of the subjects had experience with HMDs. 9 had no experience with 3D games, 6 had some, and 5 had much experience. Subjects were naïve to the experimental conditions. The total time per subject including pre-questionnaires, instructions, training, experiment, breaks, post-questionnaires, and debriefing was about 1 hour. Subjects were allowed to take breaks at any time.

4.3 Material and Methods

For the experiments we used a within-subjects design with a perception-action task based on the method of blind walking. Figure 5 illustrates the setup used during the experiment. At the beginning of each trial subjects pressed a button on a Wii remote controller, and the AR view was presented on the video see-through HMD. We instructed the subjects to walk a distance of 3m straight at a convenient speed in our laboratory, during which they received visual feedback of their real self-motion via the AR HMD. Subjects were instructed to walk towards and focus on a visual marker displayed at approximate eye height at a distance of 10m in the laboratory (see Figure 5). This instruction ensured that subjects kept their visual focus in walking direction. Targets were presented as vertical poles and shown at 3m, 4m, and 5m distance after the initial 3m walking distance. After walking the initial 3m, the HMD turned black, while subjects were instructed to walk the remaining distance to the targets without vision, and press a button on the Wii remote controller once they estimate that they have reached the middle between the verical poles. We measured the walked distance along the ground plane between the start and end positions. The display remained black until the subject was guided back to the start position to limit feedback about walked distances between trials.

The procedure extends the traditional blind walking metric for distance judgments [24] with an initial visual stimulus phase. We use this phase to augment the view on the video see-through HMD with the three optic flow transformations presented in Section 3. Each technique was parametrized to either double the optic flow speed with a gain of $g_v = 2.0$, provide a matching motion speed with a gain of $g_v = 1.0$, or half the optic flow speed with $g_v = 0.5$ (cf. Section 3). For the temporal and screen space transformations we applied $83.\overline{3}$ms inter-stimulus intervals, with $133.\overline{3}$ stimulus duration in between. For the pixel motion transformations we limited manipulations to the periphery, providing an unmodified visual focus field of about 40 degrees.

When a computer-mediated optic flow technique changes a subject's perceived self-motion velocity, we would expect the subject to walk shorter or longer to the targets, depending on the stimuli. Differences in judged walking distances for gains of $g_v = 1.0$ provide insight into general effects of the AR hard- and software on the task. Relative differences for gains of $g_v = 2.0$ and $g_v = 0.5$ reveal the potential of the techniques to change self-motion percepts. We presented all independent variables randomly and uniformly distributed over all trials. Subjects were instructed before the experiment to "ignore any and all visual modulations that may occur in the first part of the trials, and just walk to the target." We added this instruction to minimize potential experiment biases on the results that may stem from subjects anticipating the hypotheses of the experiment.

We tested each of the three techniques (*temporal*, *screen space*, *pixel motion*) with the three gains $g_v \in \{0.5, 1.0, 2.0\}$ for the three distances 3m, 4m, and 5m. Additionally, we performed the trials for the three distances using the video see-through HMD without changing the AR view with optic flow transformations, which we refer to as the *camera view* condition. Moreover, we performed the trials in the real world without HMD as a baseline *real view* condition, which we closely matched to the AR conditions by reducing the field of view using modified welding goggles, and by replacing the automatically triggered blind walking phases with auditive instructions to close the subject's eyes. The order of the trials was randomized between subjects.

We measured effects on simulator sickness with the Kennedy-Lane Simulator Sickness Questionnaire (SSQ) before and after the experiment.

4.4 Results

The results of our experiments were normally distributed according to a Shapiro-Wilk test at the 5% level. The sphericity assumption was supported by Mauchly's test of sphericity at the 5% level, or degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity. We analyzed the results with a repeated measure ANOVA and Tukey multiple comparisons at the 5% significance level (with Bonferonni correction).

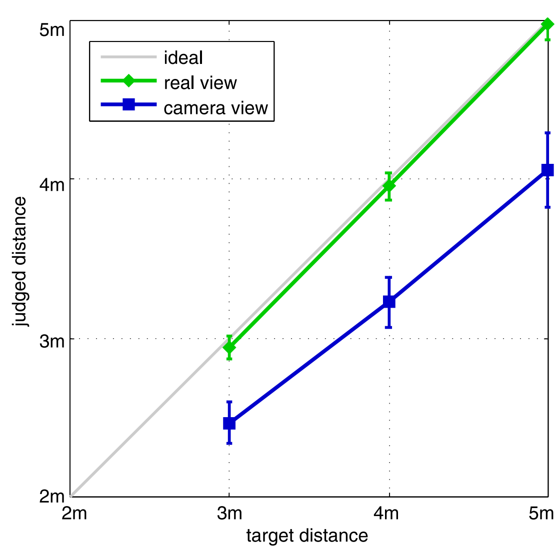
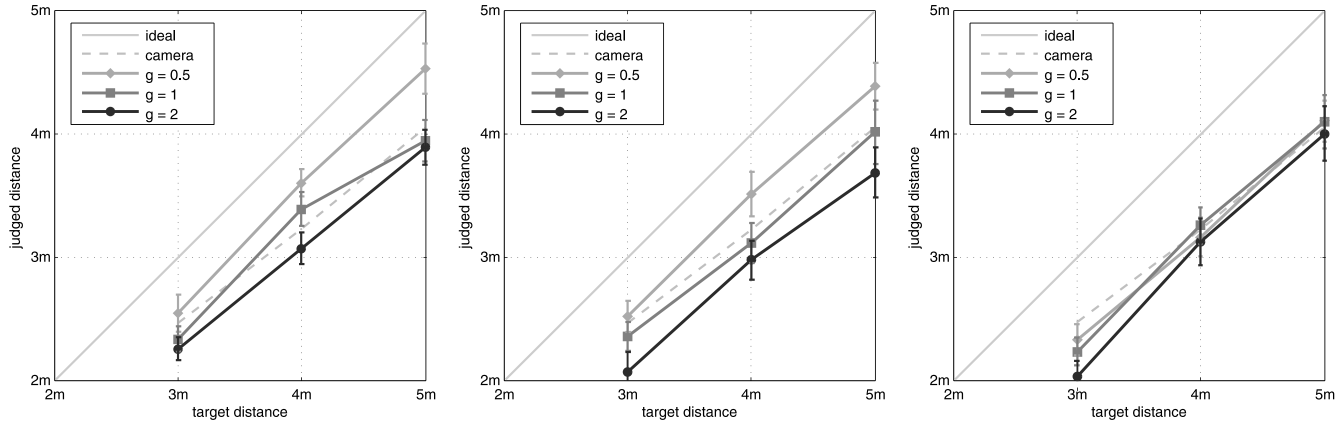


Figure 6: Results of judged walk distances in the real world and with the video see-through HMD. The green plot shows the results of the real view condition, and the blue plot of the camera view condition. The vertical bars show the standard error.



(a) temporal **(b)** screen space **(c)** pixel motion

Figure 7: Results of the judged walk distances for (a) temporal, (b) screen space, and (c) pixel motion transformations. The vertical bars show the standard error.

Real view and camera view

Figure 6 shows the pooled results for the real view and camera view conditions, i. e., the differences between performing the task in the real world compared to with the AR HMD. The *x*-axis shows the target distances, whereas the *y*-axis shows the judged walk distances. In the real world, subjects were very accurate at judging walk distances, as shown in the second column of Table 1. The walked distances with the video see-through HMD are shown in the third column of Table 1. Subjects walked approximately 18% shorter in the camera view condition than without the video see-through HMD.

We found a significant main effect of condition (F(1, 19)=28.44, p<.001, η_p^2=.60) on the walked distances. As expected, we found a significant main effect of target distance (F(1.325, 25.173)=183.37, p<.001, η_p^2=.91) on the walked distances. We found a significant interaction effect between condition and target distance (F(1.496, 28.425)=4.33, p<.05, η_p^2=.19). Post-hoc tests revealed that the walked distances were significantly shorter for the camera view condition for all target distances.

Optic flow manipulation

The pooled results for the three tested techniques are shown in Figure 7. The *x*-axes show the target distances, and the *y*-axes show the absolute walked distances. For each technique we plotted the results for the three applied gains $g_v \in \{0.5, 1.0, 2.0\}$ as well as the ideal and camera view results. Table 1 lists the mean absolute walked distances and relative to ideal judgments.

We found no significant main effect of technique (F(2, 38)=2.94, p<.66, η_p^2=.13) on the walked distances. We found a significant main effect of gain (F(2, 38)=45.86, p<.001, η_p^2=.71) on the walked distances, as well as a significant interaction effect between technique and gain (F(4, 76)=3.61, p<.01, η_p^2=.16). As expected, we found a significant main effect of target distance (F(1.332, 25.304)=228.585, p<.001, η_p^2=.92) on the walked distances. We observed no interaction effects between technique and target distance, as well as gain and target distance.

For temporal transformations, we found a significant main effect of gain (F(2, 38)=17.20, p<.001, η_p^2=.48) on the walked distances. Post-hoc tests revealed that the walked distances were significantly shorter (p<.02) for a gain of $g_v = 2.0$ compared to $g_v = 0.5$. Subjects walked approximately 18% shorter for a gain of $g_v = 2.0$ compared to $g_v = 0.5$.

For screen space transformations, we found a significant main effect of gain (F(2, 38)=26.71, p<.001, η_p^2=.58) on the walked distances. Post-hoc tests revealed that the walked distances were significantly shorter (p<.03) for a gain of $g_v = 2.0$ compared to $g_v = 0.5$.

For pixel motion transformations, we found no significant main effect of gain (F(1.538, 29.213)=1.67, p<.21, η_p^2=.08) on the walked distances. Post-hoc tests revealed no significant differences in walked distances between the tested gains.

We observed no effect of the techniques on simulator sickness. SSQ scores before the experiment averaged to 7.11, with an average post-experiment score of 7.67.

4.5 Discussion

The results shown in Figure 6 indicate that subjects significantly walked shorter with the AR HMD than in the real world. The results are in line with previous results in AR HMD environments [15, 17, 23, 45]. Although the field of view matched in both conditions, the results suggests that the weight of the HMD, low resolution, or latency in the video see-through condition may have caused a perceptual or motor difference between the conditions.

The results for temporal and screen space transformations show that judged walk distances were significantly affected by the parametrization (see Figure 7). The significantly different walked distances for temporal and screen space transformations suggest that subjects judged their self-motion as faster or slower depending on the applied gain, causing them to stop earlier or later for the fixed distances than without manipulation. As subjects had to walk at least half of the distance without vision, the results show that the computer-mediated optic flow velocity affected how subjects updated their distance to the target while walking without vision.

However, the walked distances show that visual self-motion speed estimates did not entirely dominate responses, or we would have seen subjects walking precisely twice the distance for gains of $g_v = 0.5$, and half the distance for gains of $g_v = 2$. Still, subjects' responses for $g_v = 0.5$ approximated ideal judgments in contrast to responses for natural optic flow velocities with $g_v = 1$, which suggests that computer-mediated optic flow can alleviate misperception of self-motion velocity in AR environments.

While temporal and screen space transformations require video see-through displays, we were particularly interested in the pixel motion transformations, since similar techniques could be transferred to optical see-through displays. However, effects of the tested parameters on judged walk distances were minimal. It is possible that motion cues induced by the rendering technique could be interpreted by the visual system as external motion in the scene,

Table 1: Mean absolute and relative walked distances for the different target distances, view conditions, and applied gains.

	distance	real	camera	temporal			screen space			pixel motion		
		g_v=1.0	g_v=1.0	g_v=0.5	g_v=1.0	g_v=2.0	g_v=0.5	g_v=1.0	g_v=2.0	g_v=0.5	g_v=1.0	g_v=2.0
absolute	3m	2.95	2.48	2.55	2.34	2.26	2.53	2.37	2.08	2.33	2.24	2.04
	4m	3.96	3.23	3.60	3.39	3.08	3.52	3.12	2.98	3.16	3.26	3.13
	5m	4.97	4.05	4.53	3.95	3.90	4.39	4.02	3.69	4.11	4.10	4.01
relative	3m	0.98	0.82	0.85	0.78	0.76	0.84	0.79	0.69	0.78	0.75	0.68
	4m	0.99	0.81	0.90	0.85	0.77	0.88	0.78	0.75	0.79	0.82	0.78
	5m	0.99	0.81	0.91	0.79	0.78	0.88	0.80	0.74	0.82	0.82	0.80

rather than self-motion. As suggested by Johnston et al. [16] this result could be explained by the interpretation of the visual system of multiple layers of motion information, in particular, due to the dominance of second-order motion information such as translations in a textured scene. However, this interpretation conflicts with perceptual experiments in IVEs by Bruder et al. [5], in which a similar peripheral stimulation has been found to have a strong influence on self-motion velocity estimates. The differences may be explained by the limitations of our hardware. In particular, limitations were the low resolution of the built-in cameras and the small field of view of our AR HMD (see Section 4.1), which could not stimulate a large peripheral view region. Moreover, our laboratory environment consisted mainly of gray-in-gray walls (see Figure 5), which may not have provided sufficient stimulation of retinal optic flow motion detectors in the peripheral view regions.

5 Conclusion

In this paper we analyzed self-motion perception in an AR environment and presented techniques to use computer-mediating reality to change optic flow self-motion cues. We introduced three different approaches to modify optic flow velocity: temporal, screen space, and pixel motion transformations. We presented a psychophysical experiment which shows that subjects wearing a video see-through HMD walked significantly shorter to a visual target after a phase with optic flow self-motion feedback than for the same task in the real world. This may be explained by a significant underestimation of target distances and/or overestimation of self-motion velocities while wearing the AR HMD. The experiment further showed that changing the visual self-motion velocity with the proposed computer-mediated optic flow techniques had a signficant effect on walked distances. In particular, for reduced optic flow velocities subjects' responses approached ideal judgments. The results reveal that visually augmenting head-worn displays can be used to manipulate real-world self-motion perception, i. e., users may perceive their self-motion as faster or slower than it actually is. This shows the potential of such techniques to correct self-motion misperception, or to deliberately increase or decrease self-motion velocity estimates when desired by applications.

To summarize, in this paper we have

(i) analyzed self-motion estimates with a head-worn video see-through display,

(ii) introduced *computer-mediated optic flow* to modify the perceived self-motion, and

(iii) evaluated the effects of three optic flow manipulation techniques on self-motion judgments.

In future work, we will analyze further approaches that may be used to change self-motion estimates using optic flow manipulations, in particular, using optical see-through display technologies. We aim to evaluate applications of computer-mediated optic flow for future AR setups. In particular, previous work suggests that changes in optic flow velocity can cause different locomotor behavior [28, 29, 36], including differences in muscular energy expenditure [12], which underlines the potential of visual self-motion manipulations for sports, rehabilitation, and training.

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