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THE PERCEPTION AND PRODUCTION OF SPEED DURING SELF-MOTION: EVIDENCE FOR NON-OPTIMAL COMPENSATION MECHANISMS

Coordinatore: Ch.mo Prof. Umberto Castiello

Supervisore: Ch.mo Prof. Sergio Roncato

Dottorando: Paolo Pretto

DATA CONSEGNA TESI

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Summary

The thesis describes a series of studies on the perception of speed of self-motion in realistically simulated environments. We carried out several experiments in order to explore from both the behavioral and the perceptual point of view how visual changes in the environment lead to a misperception of self-speed. More specifically, we investigated the issues of image contrast reduction, gaze direction and field-of-view and their influence on the perceived and produced speed of self-motion. Virtual environments technology was employed to display visual motion for both driving and walking speeds. Given the first results obtained from the implementation of a realistic contrast reduction in a driving simulation we formulate the hypothesis that changes in the perceived and produced speed are due to a non-optimal combination of the retinal angular velocities during self-motion. Indeed, the retinal projection of the environment during forward self-motion consists of expanding optic-flow patterns in which the angular velocities of the objects on the scene vary gradually according to their position and speed relatively to the moving observer. Objects very far away appear as moving slowly in the centre of the field-of-view, while the proximal regions appear as moving faster at the periphery of the visual field. The second part of the thesis is then dedicated to a systematic investigation on how the angular velocities from central and peripheral regions of the field-of-view contribute to the generation of the percept of a unique speed of forward translation.

In Chapter 1 we present a brief overview of the principal aspects of visual motion processing. We report some psychophysical and physiological findings that have

been produced in the last decades of research, together with some models that try to describe the functional aspects of motion and speed processing. Moreover, we introduce and explain the theme of the visual speed of self-motion. Finally, we describe the technical and methodological tools that have been adopted to implement and execute the experiments of the following chapters.

In Chapter 2 experiments are described in which we address the question how image contrast reduction affects the driving behavior. We put particular emphasis to a naturalistic implementation of contrast reduction, namely fog. We show that a realistically simulated fog causes drivers to reduce the driving speed. We provide experimental evidence that this effect has a perceptual origin, due to the increased perceived speed while driving in fog. The behavioral effect of simulated fog is consistent through different experimental setups. Moreover, we show that the effect of an increased perceived speed is enhanced accordingly to the fog density. We hypothesize an explanation for these results based on the fact that the motion signals within the visual field are selectively masked. In fact, the three-dimensional spatial distribution of the exponential fog model used in our experiments reduces mainly the visibility of the lower velocity signals, situated in the distal region of the environment, centrally in the visual field. Furthermore, we compare the effect of simulated fog to the effect of a type of contrast reduction that attenuates the visibility uniformly all over the visual field, independently of the three-dimensional structure of the environment. We demonstrate that the perception of both the driving and walking speed is independent of a spatially uniform contrast reduction and of the region within the visual field in which this reduction is applied (central or peripheral).

The experiments of Chapter 3 show that during self-motion the estimation of the self-speed relies on retinal angular velocities that are likely to be combined in a non-optimal solution. We provide evidence that the speed estimate is biased towards the available motion signals from the environment, both in the driving and in the walking speeds domain. When the visibility of the central region of the field-of-view is precluded the perceived speed is higher, and conversely, when the peripheral region is not visible, the perceived speed is lower. This suggests that the speed estimation process takes into account the velocity signals from both central and peripheral areas of the visual field. However, we provide also evidence that the central area is necessary and nearly sufficient to build a correct speed estimate, even in large field-of-view virtual environments. Finally, we report also that the speed estimate depends on the gaze direction and can be impaired when the vertical field-of-view is limited.

Summary of the results and general discussion are presented in Chapter 4.

Sommario

La tesi descrive una serie di studi sulla percezione della velocità del proprio movimento in ambienti simulati realisticamente. Sono stati eseguiti alcuni esperimenti al fine di esplorare sia dal punto di vista comportamentale sia dal punto di vista percettivo come cambiamenti visivi nell'ambiente portino ad una percezione errata della velocità. Più specificatamente, si sono analizzati alcuni aspetti relativi alla riduzione del contrasto dell'immagine, alla direzione dello sguardo e al campo visivo a la loro influenza sulla velocità percepita e prodotta del proprio movimento. La tecnologia degli ambienti virtuali è stata utilizzata per presentare il movimento visivo sia nell'ambito delle velocità compatibili con la guida sia per le velocità relative al camminare. A seguito dei primi risultati ottenuti con l'implementazione di una riduzione realistica del contrasto in una simulazione di guida si e' formulata l'ipotesi che i cambiamenti indotti nella velocita' percepita e prodotta siano dovuti ad una combinazione non ottimale delle velocita' angolari presenti a livello retinico durante il proprio movimento. In effetti, la proiezione retinica dell'ambiente durante il proprio movimento in avanti consiste in un flusso ottico di strutture che si espangono in cui le velocita' angolari degli oggetti prensenti nella scena variano gradualmente in funzione della loro posizione e velocita' relativamente all'osservatore in movimento. Oggetti molto lontani sembrano muoversi lentamente al centro del campo visivo, mentre le regioni prossimali sembrano muoversi piu' velocemente alla periferia del campo visivo. La seconda parte della tesi e' quindi dedicata ad una indagine sistematica su come le velocita' angolari provenienti dalle

regioni centrali e periferiche del campo visivo contribuiscano alla generazione del percetto di un'unica velocita' di movimento traslatorio.

Nel Capitolo 1 vengono presentati brevemente gli aspetti principali del processamento del movimento visivo. Sono riportate alcune scoperte effettuate in ambito psicofisico e fisiologico negli ultimi decenni, unitamente ad alcuni modelli che cercano di descrivere gli aspetti funzionali del modo con cui vengono processati il movimento e la velocità. Inoltre, viene introdotto e spiegato il tema della velocità visiva del proprio movimento. Infine, sono descritti gli strumenti tecnici e metodologici che sono stati adoperati per creare ed eseguire gli esperimenti dei capitoli successivi.

Nel Capitolo 2 vengono riportati gli esperimenti in cui si e' studiato come la riduzione del contrasto dell'immagine influisca sul comportamento di guida. E' stata posta particolare enfasi ad una implementazione realistica della riduzione del contrast, ossia la nebbia. Gli esprimenti mostrano come una nebbia simulata in maniera realistica induca i guidatori a ridurre la propria velocità. Viene fornita evidenza sperimentale al fatto che tale fenomeno ha origine a livello percettivo, a causa di una maggiore velocità percepita durante la guida in condizioni di nebbia. L'effetto comportamentale della nebbia simulata risulta costante anche impiegando diverse strutture sperimentali. Inoltre, si dimostra che l'effetto di una maggiore velocità percepita aumenta concordemente all'aumentare della densità della nebbia. Viene ipotizzata una spiegazione per tali risultati basata sul fatto che i segnali di movimento all'interno del campo visivo siano selettivamente mascherati. In effetti, la distribuzione spaziale tridimensionale del modello di nebbia esponenziale impiegato negli esperimenti riduce la visibilità principalmente dei segnali di movimento a bassa velocità, situati nella regione distale dell'ambiente, centralmente nel campo visivo. Inoltre, l'effetto della nebbia simulata viene comparato con l'effetto di un tipo di riduzione del contrasto che attenua uniformemente la visibilita' sull'intero campo visivo, indipendentemente dalla struttura tridimensionale dell'ambiente. Si dimostra quindi che la percezione della velocità di guida e della camminata sono indipendenti da una riduzione spazialmente omogenea del contrasto e dalla regione del campo visivo a qui tale riduzione si applica (centrale o periferica).

Gli esperimenti del Capitolo 3 mostrano che durante il proprio movimento la stima della propria velocità lineare si basa su velocità angolari presenti a livello retinico che probabilmente vengono integrate in maniera non ottimale. Viene mostrato come la stima della velocità sia influenzata dai segnali di movimento disponibili nell'ambiente, sia nell'ambito delle velocità di guida sia di quelle del camminare. Quando la visibilita' della regione centrale del campo visivo e' preclusa la velocita' percepita risulta maggiore e, inversamente, quando la regione periferica non e' visibile, la velocita' percepita appare inferiore. Questo suggerisce che il processo attraverso il quale viene stimata la velocità prenda in considerazione le informazioni di movimento provenienti sia dalle aree centrali sia dalle aree periferiche del campo visivo. Infine, e' riportato anche il fatto che la stima della velocità dipende dalla direzione dello sguardo e può essere deteriorata quando il campo visivo verticale è limitato.

Il sommario dei risultati e la discussione generale sono presentati nel Capitolo 4.

Zusammenfassung

In dieser Arbeit werden eine Reihe von Studien zur Wahrnehmung der Geschwindigkeit der Eigenbewegung in realistisch simulierten Umgebungen beschrieben. In mehreren Experimenten wurde die Wahrnehmung und das Verhalten daraufhin untersucht, ob visuelle Änderungen in der Umwelt zu einer Fehlwahrnehmung der eigenen Geschwindigkeit führen. Im Speziellen wurde der Einfluss des Bildkontrasts, der Blickrichtung und der Größe des Sichtfelds auf die wahrgenommene und produzierte Geschwindigkeit bei Eigenbewegung bestimmt. Die visuelle Bewegung wurde mit Hilfe der Technik der virtuellen Realität dargeboten, und lag im typischen Bereich von Geh- und Fahrgeschwindigkeiten.

Die ersten Ergebnisse in einer Fahrsimulation mit realistischer Kontrastreduktion zeigen einen Einfluss auf die wahrgenommene und produzierte Geschwindigkeit, und es wird die Hypothese formuliert, dass eine suboptimale Kombination der retinalen Winkelgeschwindigkeiten dem beobachteten Effekt zu Grunde liegen könnte. Die Projektion der Umwelt auf der Retina ist während einer geradlinigen Vorwärtsbewegung ein expandierendes optisches Flussmuster, und in diesem hängt die Winkelgeschwindigkeit eines Objekts von seiner Position und Geschwindigkeit relativ zum Beobachter ab. Entfernte Objekte im Zentrum des Sichtfelds scheinen sich entprechend langsam zu bewegen, während nahe Regionen in der Peripherie des Gesichtsfelds als schneller erscheinen. Der zweite Teil der Arbeit widmet sich mit systematischen Untersuchungen der Frage, welchen Anteil die unterschiedlichen Winkelgeschwindigkeiten aus dem zentralen und peripheren Sichtfeld bei der

Entstehung einer eindeutigen Geschwindigkeit in der Wahrnehmung während der Vorwärtsbewegung haben.

In Kapitel 1 wird eine Übersicht über die wichtigsten Aspekte der Verabeitung von visueller Bewegung präsentiert. Es werden psychophysische und physiologische Befunde der letzten Jahrzehnte dargestellt, zusammen mit Modellen, die die funktionalen Aspekte der Bewegungs- und Geschwindigkeitsverarbeitung verdeutlichen. Zudem wird das Thema der visuellen Geschwindigkeit während der Eigenbewegung eingeführt und erläutert. Schließlich beschreibt das Kapitel die technischen und methodologischen Hilfsmittel zur Umsetzung und Durchführung der Experimente in den nachfolgenden Kapiteln.

Die Experimente in Kapitel 2 befassen sich mit der Frage, wie Kontrastreduktion das Fahrverhalten beeinflusst. Besonderen Wert wurde in diesen Experimenten auf eine möglichst natürliche Implementierung der Kontrastreduktion in Form von Nebel gelegt. Es konnte gezeigt werden, dass realistisch simulierter Nebel die Fahrer veranlasst, ihre Fahrgeschwindigkeit zu reduzieren. Es wird experimentelle Evidenz dafür geliefert, dass dieser Effekt perzeptuelle Ursachen hat und aufgrund einer erhöhten wahrgenommenen Geschwindigkeit während der Nebelfahrt auftritt. Der Einfluss von simulierten Nebel auf das Verhalten ist über verschiedene experimentelle Aufbauten hinweg konsistent zu beobachten. Weiterhin wird gezeigt, dass der Effekt mit zunehmender Nebeldichte verstärkt wird. Der Umstand, dass die Bewegungssignale innerhalb des Gesichtsfelds durch Nebel selektiv maskiert werden , bildet den Ausgangspunkt für eine Erklärung dieser Ergebnisse.

Tatsächlich reduziert die dreidimensionale räumliche Verteilung des in diesen Versuchen verwendeten exponentiellen Nebelmodels vorallem die Sichtbarkeit der niedrigeren Geschwindigkeitssignale aus den entfernteren Teilen der Umwelt und im zentralen Gesichtsfeld. Im Anschluss wird simulierter Nebel mit einer weiteren Art von Kontrastreduktion verglichen, welche die Sichtbarkeit gleichförmig über das gesammte Gesichtsfeld reduziert und unabhängig von der dreidimensionalen Struktur der Umwelt ist. Es wird gezeigt, dass die Wahrnehmung von Fahr- und

Gehgeschwindigkeiten nicht durch eine räumlich gleichförmige Kontrastreduktion beeinflusst wird, und auch nicht vom Gesichtsfeldbereich abhängt, in dem diese Kontrastreduktion stattfindet.

Die Experimente in Kapitel 3 zeigen, dass die Schätzung der Geschwindigkeit während der Eigenbewegung im Zusammenhang mit einer suboptimalen Kombination der retinalen Winkelgeschwindigkeiten steht. Es wird hierbei gezeigt, dass die Geschwindigkeitsschätzung in Richtung der aus der Umwelt zur Verfügung stehenden Bewegungssignale systematisch beeinflusst wird, und bei normaler Gehgeschwindigkeit wie auch bei typischen Fahrgeschwindigkeiten auftritt. Wenn die Sicht auf das zentrale Sichtfeld verhindert wird, ist die wahrgenommene Geschwindigkeit höher, und analog dazu erniedrigt sich die wahrgenommene Geschwindigkeit, wenn der periphere Bereich nicht sichtbar ist. Dieser Befund deutet darauf hin, dass im Prozess der Geschwindigkeitsschätzung die Geschwindigkeitssignale sowohl von der Peripherie wie auch von zentralen Bereichen des Gesichtsfelds berücksichtigt werden. Es werden aber auch Hinweise vorgelegt, dass der zentrale Bereich notwendig und nahezu ausreichend ist, um zu einer korrekten Geschwindigkeitsschätzung zu gelangen, selbst in virtuellen Umgebungen, die über ein großes Sichtfeld verfügen. Schließlich wird aufgezeigt, dass die Geschwindigkeitsschätzung von der Blickrichtung abhängt, und beeinträchtigt werden kann, wenn das vertikale Sichtfeld eingeschränkt wird.

Die Zusammenfassung der Ergebnisse und die generelle Diskussion erfolgt in Kapitel 4.

Chapter 1

Introduction

The aim of this work was to investigate the perception of the speed of self-motion in realistically simulated environments. We carried out several experiments in order to explore from both the behavioral and the perceptual point of view how visual changes in the environment lead to a misperception of self-speed. More specifically, we investigated the issues of image contrast reduction, gaze direction and field-of-view [1] and their influence on the perceived and produced speed of self-motion. Virtual environments technology has been exploited in order to visually simulate driving scenarios and walking speeds.

In this chapter we provide a brief overview of the main characteristics of visual motion. We present some psychophysical and physiological findings that have been produced in the last decades of research, together with some models that try to capture the functional aspects of motion and speed processing. Moreover, we introduce and explain the theme of the visual speed of self-motion, which is the main topic of this dissertation. Finally, we describe the technical and methodological tools

[1] In this thesis we use the term *field-of-view* to indicate the displayed area when viewed through an optic. Whereas, the term *visual field* is used to indicate the visible area subtended by the human eye.

that have been adopted to implement and execute the experiments of the following chapters.

1.1. Visual motion and speed perception

Motion is the displacement of something over time. Visual motion is the displacement of a visual image over time. Although it is still debated whether motion can be qualified as a fundamental biological sense, there are no doubts that it is indeed a fundamental visual dimension. Visual motion perception is the process by which we analyze the motion of objects and surfaces in the image. Visual motion perception serves several perceptual purposes (Albright & Stoner, 1995; Movshon, Adelson, Gizzi, & Newsome, 1985; Nakayama, 1985). The main goal of the motion processing apparatus is, intuitively, to recover and represent the trajectories of objects in a form that facilitates behavioral responses to those movements (Gibson, 1950). The direction and velocity of motion is then reconstructed by the visual motion system. This system is also a source of information for the encoding of the three-dimensional (3D) structure of a visual scene (von Helmholtz, 1924; Nakayama & Loomis, 1974; Wallach & O'Connell, 1953). It allows the control of posture (Bardy, W. H. Warren, & B. A. Kay, 1999; Gibson, 1950; W. A. Lee, 1980) and the estimation of the heading direction (Koenderink, 1986; Lappe, Bremmer, & van den Berg AV, 1999). Motion is also used to detect the time-to-collision (TTC) from the rate of expansion of the optical flow field (the two-dimensional array of local translational velocities) (Schrater, Knill, & E. P. Simoncelli, 2001; Todd, 1981). Motion allows also the parsing of complex pattern of illumination in the optic array into different physical objects and to distinguish figure from the background (Jia, Jia, & Balasuriya, 2005; Nakayama & Loomis, 1974). This concept was originated by the well-known Gestalt principle of “common fate” where points moving at the same velocity are perceived as a coherent entity distinguishing it from background and other objects (Koffka, 1935). To study motion-sensitive mechanisms, the psychophysical methods developed in the last decades were used to measure performance indicators, such as motion sensitivity, direction discrimination and speed discrimination (see Nakayama, 1985 for a review). In the next two paragraphs we briefly describe the main anatomical areas and pathways involved in the motion processing and some of the models that have been proposed to account for different psychophysical results.

1.1.1. Visual motion areas

The main visual area of the human brain is the primary visual cortex, called V1. See the visual areas of the human brain at Figure 1.1.

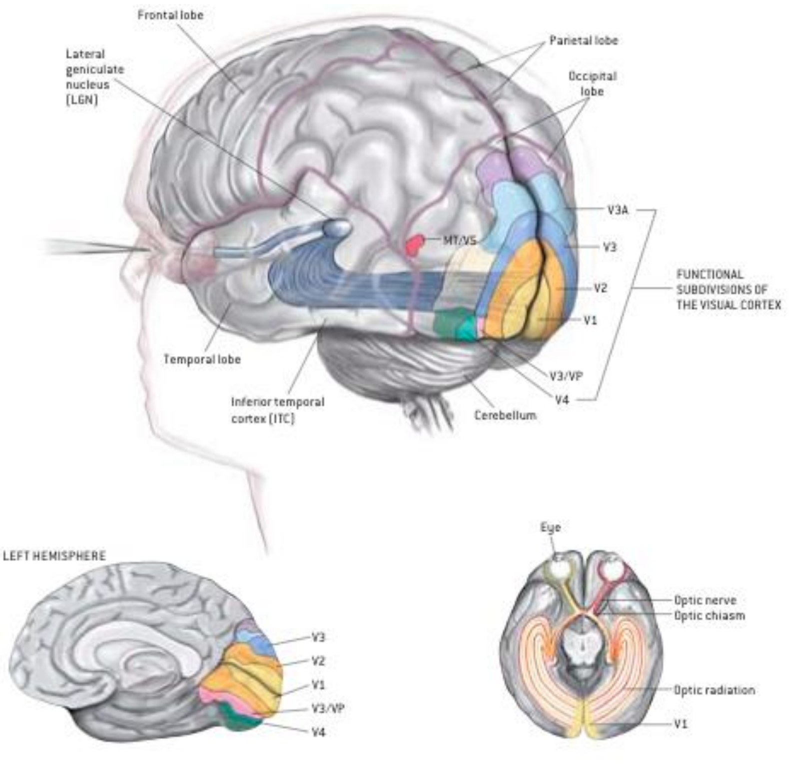

Figure 1.1: The human visual areas (Logothetis, 1999). From the eyes and through several brain structures before ascending to the various region of the visual cortex through different pathways.

Motion-selective and direction-selective cells were found by single-cell recording techniques in primates in V1 (Hubel & Wiesel, 1977). Neurons in the magno-cellular pathway have fast and transient responses, allowing detection and encoding of movements in the later stages of the pathway. Within the magno-recipient area there are progressively more direction-selective cells that have been found in the areas of V1 to V3 (Felleman & Van Essen, 1987). Many researches in neurophysiology of visual-motion are concentrated on MT (Middle Temporal area, or V5) and MST (Medial Superior Temporal area), both are in the superior temporal sulcus of the macaque (for a review (Culham, Verstraten, Ashida, & Cavanagh, 2000). Almost all MT neurons exhibit directionally selective responses. Recordings on monkeys from MT show a close correlation between direction discrimination and the activity of motion-selective cells in MT. Area MT projects directly to MST- an area containing also a high proportion of directionally selective cells, which respond also to rotation, expansion and contraction. It was found that in the macaque MT also sends projections to other motion areas of the brain: FST, VIP and STP (Figure 1.2).

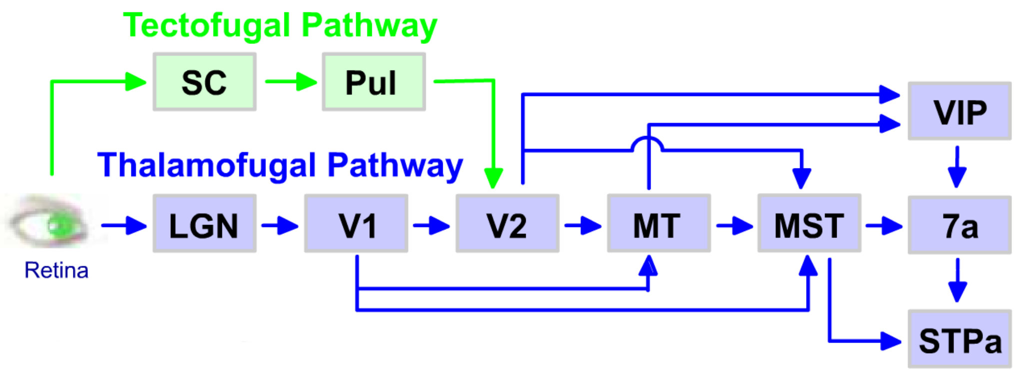

Figure 1.2: (adapted from http://www.psych.ualberta.ca/~iwinship/vision/navmap.htm) The human visual pathways. Ventral (Thalamofugal) Pathway in blu, Dorsal (Tectofugal) Pathway in green.

Recent experiments of neuroimaging using non-invasive Functional Magnetic Resonance Imaging (fMRI) technique allowed experiments with human subjects to confirm the physiological and anatomical results obtained by the invasive electrophysiological single-cell recording technique, which obviously couldn't be used on human subjects. The fMRI results have shown that the dorsal pathway is a major route for motion analysis (Culham, He, Dukelow, & Verstraten, 2001). Neuroimaging revealed that area V5 is presumably the human homolog to the monkey's MT, MST and adjacent motion selective cortex. fMRI revealed that V5 is easily and consistently activated in the human brain responding to a wide range of dynamic stimuli (Tootell et al., 1995).

The neuroanatomical areas described so far are involved at different stages of motion processing and they are responsible for different features of the visual stimuli. A more detailed description of some of the functions accomplished by these areas is reported in section 1.2.

1.1.2. Architecture of visual motion processing

As we said, the main goal of the motion processing system is to compute the speed and direction of image motion from the changes in the retinal image over time. Therefore, motion processing requires both temporal image processing as well as spatial processing. It is well known from phenomena like the motion after-effect (MAE) and the "persistence of vision" (Barlow & Hill, 1963; Mather, 1988) that neurons in the visual system summate information over time as well as space. Thus, we need to think of receptive fields as being spatiotemporal filters and of motion as being a vector in the spatiotemporal domain. As a general mechanism, the motion analysis allows the reconstruction of velocity (speed and direction) field by the temporal integration of the spatial-filtered feature determined locally in a previous stage of the process. In this section we shortly describe the stages of motion processing and some motion sensors.

A first subsystem ("feature tracking") of the motion processing is dedicated to the analysis of retinal motion by local orientation-selective motion sensors that infer motion from changes in the retinal position of objects over time (E. H. Adelson & Bergen, 1985; Del Viva & Morrone, 1998; van Santen & Sperling, 1985; Ullman, 1979; Watson & Ahumada, 1985). These sensors respond to motion of luminance-defined features in a particular direction ("first-order" motion stimuli). Two-dimensional arrays of these sensors should in principle account for different motion directions (E. H. Adelson & Movshon, 1982). A 'second-order' motion system (Lu & Sperling, 1995) is based on sensors that respond to the motion of patterns defined by spatial modulation of local contrast or of other image properties.

In the following sections we introduce three different detectors that have been developed. We consider the motion detector as a device that responds selectively to the representations of motion shown in Figure 1.3.

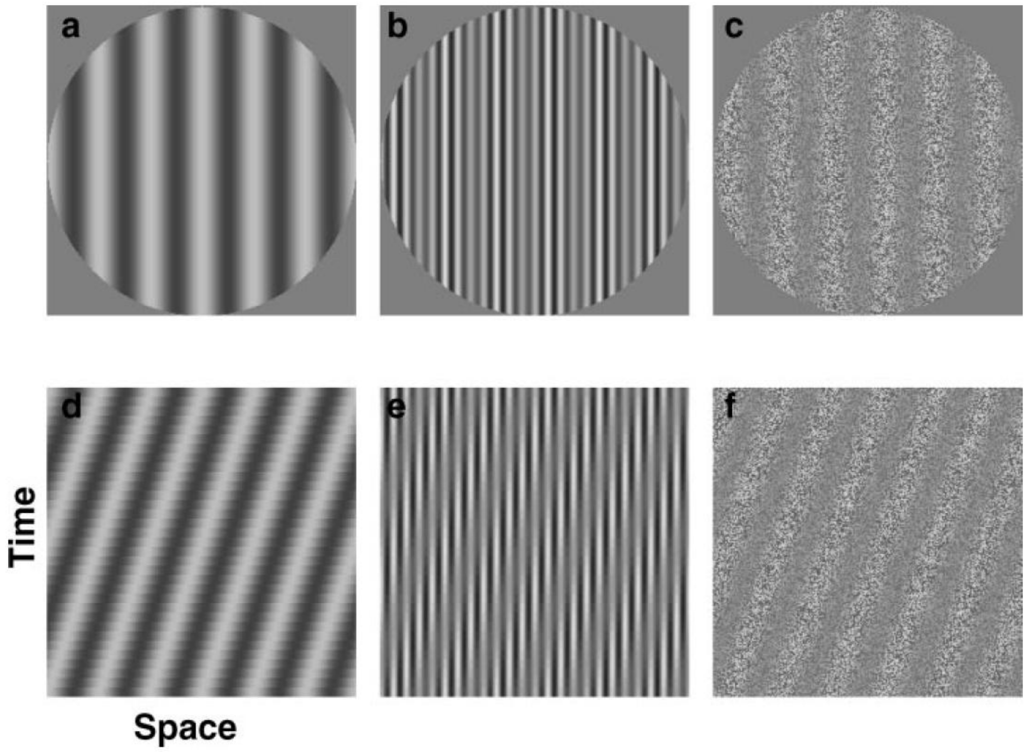

Figure 1.3: Contrast and luminance patterns (upper panels) and space-time plots of their motion (lower panels). (*a*) A sinusoidal grating. (*b*) A second-order stimulus, contrast-modulated grating. It is the product of a stationary high spatial frequency luminance grating (the "carrier") and a moving sinusoidal modulation (the "envelope"), which causes the contrast of the carrier to vary across its surface. (*c*) A contrast-modulated dynamic random dot pattern. The envelope is identical to that in (*b*) but the carrier is a random dot pattern. (*d*) A space-time plot of (*a*) The reciprocal of the gradient (displacement/time) gives the speed of motion. (*e*)

Space-time plot of (*b*). Note that only the contrast modulation (the envelope) moves. (*f*) Space-time plot of (*c*). Note that the envelope motion is like (*e*) but that the dot pattern changes on every frame (A. M. Derrington, Allen, & Delicato, 2004).

The correlation model, also known as Reichardt detector (Reichardt, 1961), as shown in Figure 1.4, was developed from the observation that two interacting omnatidia in the eye of a fly can code for space and time and, therefore, for motion.

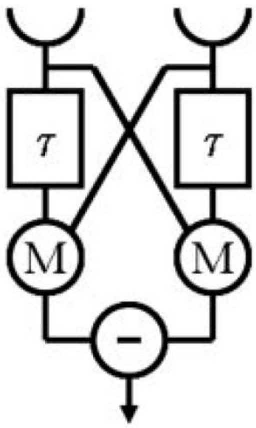

Figure 1.4: Reichardt detector. The Reichardt detector consists of two mirrorsymmetrical subunits. In each subunit, the luminance values as measured in two adjacent image locations become multiplied (M) with each other after one of them is delayed by a low-pass filter with time-constant τ. The resulting output signals of the multipliers become finally subtracted (from (Haag, Denk, & Borst, 2004)).

This sensor derives a motion signal by spatio-temporal correlation of luminance signals from neighboring points in the image. When a luminance pattern moves along the axis connecting the two points (s) then the signal at one point will be a time-shifted version of the signal at the other (see Figure 1.4). The correlation approach has been used to account for aspects of human motion perception and to explain the physiological properties of direction-selective neurons (van Santen & Sperling, 1984, 1985).

The second approach is called “motion-enery” model, and it consists of receptive fields selective for orientation in space-time (E. H. Adelson & Bergen, 1985; Watson & Ahumada, 1985). Oriented spatio-temporal receptive fields sense motion because, as Figure 1.3 shows, the gradient in a space-time plot indicates the speed and direction of motion. The motion energy filter gives no direct information about velocity. The filter’s output depends on contrast, spatial frequency, and temporal frequency. For any given stimulus there is an optimal velocity, but the optimal velocity depends on the stimulus.

A third approach to designing a motion sensor (“gradient’ model) is to take the ratio of the temporal and spatial gradients of luminance in the moving image (Fennema & W. B. Thompson, 1979; Johnston, McOwan, & Buxton, 1992). In fact, the spatial variations in luminance in a moving image cause temporal variations. Assuming that all the temporal variation in a space-time image is caused by movement, the relation between spatial and temporal variations at any position allows to detect the motion exactly. The gradient motion sensor works because the temporal gradient is generated by the product of the spatial gradient and the velocity, so the ratio of the two gradients gives the velocity directly. Gradient-based motion sensors are also sensitive to the motion of contrast-envelopes (Benton, 2002).

Both psychophysical and physiological evidences suggest that motion sensors described are selective for orientation (Anderson, Burr, & Morrone, 1991; Hubel & Wiesel, 1968), and therefore, can only analyze motion in one dimension: along an axis orthogonal to the sensor’s preferred orientation. A second stage of motion analysis is used to compute the direction of motion of a 2-D pattern (E. H. Adelson & Movshon, 1982; Fennema & W. B. Thompson, 1979). How are the 1-D motion signals from sensors tuned to different orientations combined to produce an unambiguous 2-D motion signal? The typical 2-D pattern extensively used in psychophysical research on 2-D motion analysis is the plaid pattern Adelson & Movshon (1982), made by summing two sinusoidal gratings of different orientations. From series of psychophysical and physiological studies (Champion, Hammett, & P.

G. Thompson, 2007; A. M. Derrington & Badcock, 1992; A. M. Derrington, Lennie, & Wright, 1979; Ferrera & Wilson, 1987; Tinsley et al., 2003) it has been established that 2-dimensional motion analyses must use signals from localized broadly oriented motion sensors.

We will see in the paragraph 1.3 how the third dimension of the visual stimuli, which is actually the more natural condition of stimulation, changes the perception of both the objects- and the self-motion through the environment. Before that, we want to illustrate more the topic of the perceived speed, and especially referring to how recent models of visual motion perception try to account for the dependency on image contrast of the perceived speed.

1.1.3. The dependence on contrast of the perceived speed

Psychophysical studies on two-dimensional motion perception have shown that observers can misestimate speed when image texture (Blakemore & Snowden, 2000) or luminance (Takeuchi & De Valois, 2000) are reduced. Spatio-temporal characteristics of the image (McKee & Welch, 1989) and eye movements (Wertheim, 1994) are also thought to influence the perceived speed of translational motion. An extensively studied perceptual factor that has been shown to affect the perceived speed of 2-D moving objects is the contrast of the scene (Hawken, Gegenfurtner, & Tang, 1994; L. S. Stone & P. Thompson, 1992; P. Thompson, 1982). Since Thompson (1981) first reported that perceived speed depends on stimulus contrast there have been many papers that have supported his findings that at slow speeds (below 4 deg/s) a reduction of contrast reduces the perceived speed (Blakemore & Snowden, 1999; K. Brooks, 2001; Hürlimann, Kiper, & Carandini, 2002; Müller & Greenlee, 1994). It has also been reported that for high temporal frequencies (above 8 cycle/s) reducing the contrast results in speed being overestimated (Hawken et al., 1994; P. Thompson, 1982). A model of motion perception that can specifically account for the effect of contrast on perceived speed is needed. In the next section we describe two recent computational models of speed processing.

1.1.3.1. *The Bayesian model*

Weiss, Simoncelli, and Adelson (2002) stated that a Bayesian model can describe the behavior of a human observer and predict human visual speed perception.

The optimal Bayesian observer may be precisely formulated in terms of two probability distributions. A conditional probability distribution, which describes the variability of a set of measurements, is known as a likelihood function. The second component is a prior probability distribution, which specifies the probability of encountering stimuli moving at any particular speed. According to Bayes' rule, the product of these two components gives the posterior distribution, which should correspond to the detected speed by an optimal observer. In other words, human visual speed perception is assumed as qualitatively consistent with a Bayesian observer that optimally combines noisy measurements of speed with a prior preference for lower speeds.

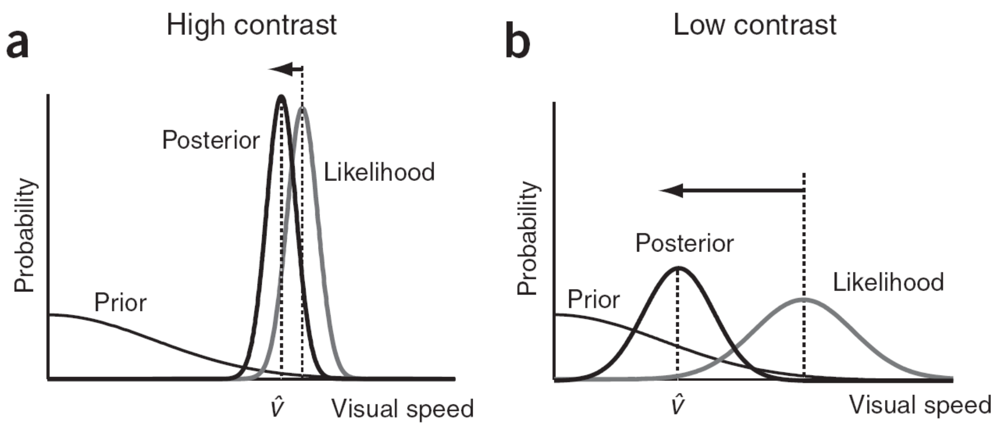

Figure 1.5: Bayesian model of visual speed perception accounting for contrast-induced biases in speed perception (Stocker & E. P. Simoncelli, 2006). (a) A stimulus with high contrast leads to relatively precise measurements and thus a narrow likelihood. Multiplication by a prior probability for low speeds induces only a small shift of the posterior relative to the likelihood. (b) A low-contrast stimulus is assumed to produce noisier measurements and thus a broader likelihood. Multiplication by the same prior induces a larger shift and thus the low contrast stimulus is typically perceived as moving slower.

A recent implementation of such a Bayesian model (Stocker & Simoncelli, 2006), where the noise is approximately proportional to the stimulus speed and depends inversely on stimulus contrast, accounts for the variability of subjective responses in a speed discrimination task (Figure 1.5). However, this model and similar ones (Ascher & Grzywacz, 2000) does not predict any increase in speed at reduced contrasts, as reducing contrast always increases the influence of a slow speed prior. In a slightly different implementation of the same Bayesian model, Hürlimann, Kiper and Carandini (2002) have shown that, with a non-linear dependence of response on contrast, such a model can make quantitative predictions on the perceived speed of drifting gratings and its dependence on contrast.

1.1.3.2. The Ratio model

Some experiments (Thompson, 1976, 1982; (P. G. Thompson, L. S. Stone, & K. Brooks, 1995); Blakemore & Snowden, 1999) found evidence that at higher velocities, perceived speed may be over-estimated as contrast falls. Thompson (1982) proposed that velocity was computed by a ratio of a high speed channel and a slow speed channel (Harris, 1986), and that reducing contrast would reduce the influence of the high speed channel at low speeds and reduce the influence of the low speed channel at high speeds. In this model the computation of speed is based on the ratio of a low pass and a band pass temporal filter described by Perrone (J. A. Perrone, 2005). The model employs physiologically plausible temporal filters and assumes that speed is encoded as the ratio of the output of those two speed channel that have been recently proposed (Hammett, Champion, Morland, & P. G. Thompson, 2005). The fitting of the model to real data is shown in Figure 1.6.

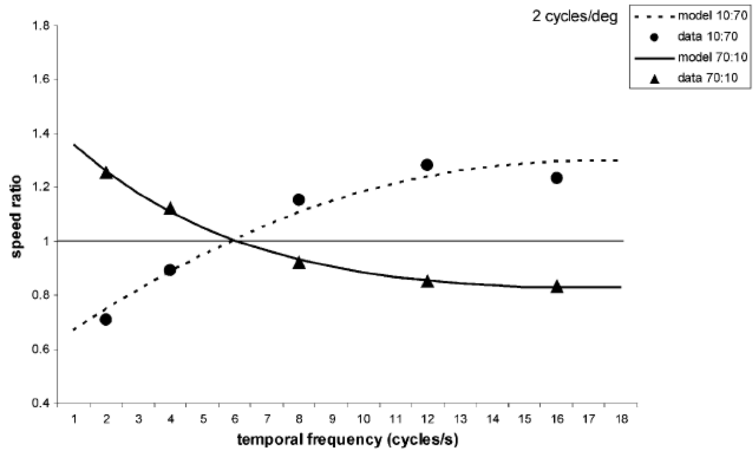

Figure 1.6: The best fit of ratio model to experimental data. Speed is matched at different contrasts (P. Thompson, K. Brooks, & Hammett, 2006). All stimuli 2 cycles/deg. Filled circles show speed matches of 0.7 contrast gratings stair-cased to match speed of 0.1 contrast standard. Filled triangles show speed matches of 0.1 contrast gratings stair-cased to match speed of 0.7 contrast standard. Lines show the fitting of the model to the real data. Lower contrast stimuli appear slower at low temporal frequencies (2 and 4 cycles/s) but appear to move faster at higher temporal frequencies (12 and 16 cycles/s).

1.1.4. Role of central and peripheral vision in motion perception

Three theories have been proposed in the last decades to explain the role of central and peripheral vision for the perception and control of self-motion. The *peripheral dominance hypothesis* states that peripheral vision dominates the perception of self-motion, whereas the central region dominates the perception of object-motion (Brandt, Dichgans, & Koenig, 1973; Berthoz, Pavard, & Young, 1975). The *functional sensitivity hypothesis* proposes that self-motion and object-motion are perceived on the basis of optical information but the central vision is sensitive to radial and lamellar flow patterns, whereas peripheral vision is sensitive to lamellar flow and not to radial flow (W. H. Warren & Kurtz, 1992). A third theory, the *retinal invariance hypothesis,* states that both self- and object-motion are perceived on the basis of information in optic-flow, independently of the eccentricity of stimulation (Crowell & Banks, 1993). A study on postural control states for the last hypothesis, indicating that control principle for posture during locomotion is based primarily on the structure of the optic-flow pattern, regardless of its retinal eccentricity (Bardy et al., 1999). Another recent study on the perception of motion direction indicates also that central and peripheral vision provide equal input to the mechanism underlying the perception of optic-flow (Habak, Casanova, & Faubert, 2002). However, the authors have found also that an asymmetry may arise when strong signals are presented in one region and weak signals in the other. For direction discrimination, strong signals from periphery facilitate the percept when central signals are weaker, but not the reverse.

1.2. Optic-flow and self-motion perception

When an observer moves through the world, the retinal projection of the forward self-motion consists of expanding (radial) optic flow patterns (Gibson, 1950). In other words, the optic-flow can be described as the visual motion of objects as the observer moves relative to them. To an observer driving a car, a sign on the side of the road would move from the center of his field-of-view to the side, growing as he approached. The field-of-view (FOV) indicates the visible area of a human observer. Gibson was the first to realize that the optic-flow patterns constitute a rich source of information about both our movement through, and the three-dimensional structure of the environment. The visual flow field generated in the retina during walking or driving depends on both the direction of travel and the direction of gaze. More specifically, during self-motion, the pattern of the optic flow can be of three kinds: radial patterns, in which the image seems to expand from the focus of expansion, generated by forward motion; translational patterns, generated by fronto-parallel motion (moving left and right); and spiral patterns, produced by rotation (Koenderink & van Doorn, 1986). Normally, self-motion through the environment is a combination of several types of movement and the resulting optic flow is a combination of these different patterns (Figure 1.7).

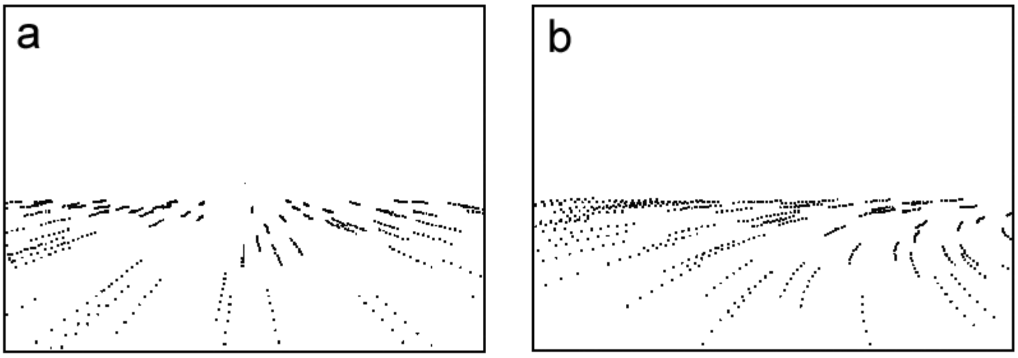

Figure 1.7: Optic-flow patterns during self-motion. Forward translation induces a radial pattern (a), forward translation and rotation induces a spiral pattern (b).

In the optic-flow field (the two-dimensional field of local velocities) the angular[2] velocities of the objects on the scene vary gradually according to their position and speed relatively to the moving observer. The velocity flow field generated during self-motion is important for spatial orientation and visual navigation (Bruggeman, Zosh, & W. H. Warren, 2007; Royden, Crowell, & Banks, 1994; W. H. Warren & Hannon, 1988; W. H. Warren, Morris, & Kalish, 1988; W. H. Warren, B. A. Kay, Zosh, Duchon, & Sahuc, 2001). In an expanding optic-flow field, the rate of this expansion conveys information about the observer's speed (Clifford, Beardsley, & Vaina, 1999) and the time-to-collision (Kaiser & Hecht, 1995; D. N. Lee, 1976; Schiff & Detwiler, 1979). The role of optic flow has been demonstrated also for the perception and control of speed during walking (Baumberger, Fluckiger, & Roland, 2000), flying (Larisch & Flach) and driving (Kemeny & Panerai, 2003; M. F. Land & D. N. Lee, 1994). During walking, for example, changes in the velocity of the visual ground, thus altering the optic flow, lead to unintentional modulation of walking speed (Prokop, Schubert, & Berger, 1997): a backward flow leads to a decrease in walking speed, whereas a forward flow leads to an increase in walking speed.

[2] *Angular* refers to the angle subtended at the retina, so that the units of angular velocity are degrees subtended at the retina per second (deg/s).

Psychophysical (Morrone, Burr, Di Pietro, & Stefanelli, 1999) and physiological (Duffy & Wurtz, 1991; Orban et al., 1992) studies have provided evidence that these expansionary motions are processed by specialized mechanisms in the visual system. It is commonly assumed that the rate of expansion is estimated from the divergence of the optic-flow field (Crowell & Banks, 1993; Gibson, 1950; J. A. Perrone, 1992; W. H. Warren et al., 1988). Although Schrater *et al.* (2001) have demonstrated that the visual system contains mechanisms that are explicitly sensitive to changes in scale *per se* and that are used to estimate the observer's speed and time-to-collision.

The analysis of motion in the optic array is complicated by the fact that the eyes and the head move with respect to the body, and these movements are superimposed on body movements. The result is a retinal motion pattern that is composed of translational (head and body movement) and rotational (eye movement) components. One therefore has to distinguish retinal flow from optic flow, and note that the visual system has to use retinal-, not optic-flow as the basis of self-motion estimation (Cutting, Springer, Braren, & Johnson, 1992; Regan & Beverly, 1982; W. H. Warren & Hannon, 1988). Moreover, the structure of retinal flow also depends on the distances of the visible objects from the observer. Retinal flow is often very different from the simple expansion pattern of optic flow. Typical cases that have been used in studies of heading detection are shown in Figure 1.8.

Vestibular and proprioceptive sensory feedback and efference copies of body, head, and eye movements usually help to disambiguate object- from self-motion (Wertheim, 1994; Wexler, Lamouret, & Droulez, 2001). However, when visual-motion is the sole informative cue for reconstructing self-motion the illusion of self-motion (vection) may arise (Dichgans & Brandt, 1978). In many psychophysical and behavioral experiments self-motion perception is illusory as the experimental setup is placed statically in a laboratory and that might precludes true observer-motion. However, this model to study visual processing during self-motion is valid because afferent input during vection imitates that from constant-velocity self-motion. A constant motion (without acceleration) of the observer will not provide any vestibular or proprioceptive input. For instance, while driving a car at constant velocity and fixating the end of a straight road, reconstruction of self-motion will exclusively depend on visual motion processing (Kleinschmidt et al., 2002).

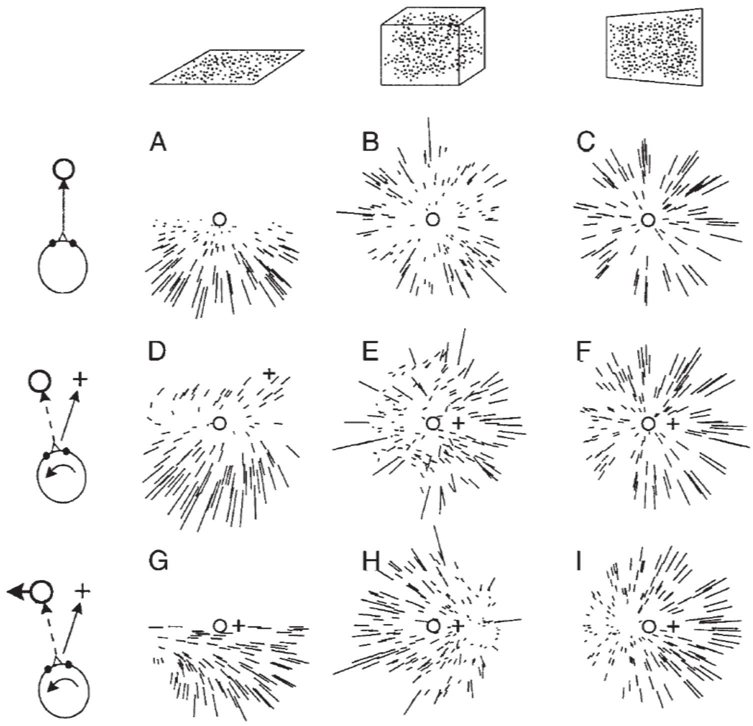

Figure 1.8: (Lappe et al., 1999) Retinal-flow fields. The retinal flow experienced by a moving observer depends on translation, eye rotation, and the 3-D structure of the environment. Columns represent different environments: a flat horizontal plane (the 'ground plane'), a 3-D volume random dots, and a vertical wall. Rows represent different combinations of observer translation and eye rotation. (A–C) Pure forward movement in the absence of eye movement. The flow consists of a radial expansion. All motion is away from the focus of expansion which indicates heading. (D–F) Forward movement while gaze is directed towards an element in the environment. Heading is indicated by a cross, direction of gaze by a circle. An eye rotation is necessary to stabilize gaze onto the target element. The direction of this eye movement is coupled to the motion of the observer. In the ground plane (D), the retinal flow becomes spiral. (E) motion parallax: dots near the observer move fast and follow an expansion pattern. Their motion is dominated by the forward movement. Dots far from the observer move more slowly and in a more laminar pattern. Their motion is dominated by the eye rotation. The vertical wall (F) is a special case: the uniform motion introduced eye movement transforms the flow field such that a new focus of expansion appears in the direction of gaze (circle). Often human subjects confuse this flow field with that of forward movement (C) but the distribution of speeds at the periphery is different. (G–I) Forward movement (cross) with an eye rotation

towards a horizontally moving target (circle). This target is not attached to the environment, thus direction of the eye movement is uncoupled from heading. In G and I eye movement towards the left, in H to the right.

As seen in the previous section, several models are available to compute local translational motion. It has been shown (Grzywacz & Yuille, 1990; Heeger, 1987; Smith & Edgar, 1994) that an estimate of local velocity is encoded by spatial (De Valois & Switkes, 1980) and temporal (Foster, Gaska, Nagler, & Pollen, 1985) selectivity of cells in primate visual cortex. Overall speed can be determined from these spatio-temporal properties. The question is then how higher level optic-flow mechanisms might use local motion signals to encode self-motion and 3-D structure of the image. Several hierarchical models of optic-flow have been proposed to determine the focus of expansion and the direction of heading (Lappe & Rauschecker, 1995; Zhang, Heuer, & Britten, 2004). This hierarchical approach is supported by a number of electrophysiological studies in primate visual cortex showing sensitivity to more complex patterns of motion at higher stages of visual processing (Maunsell & Van Essen, 1983). Translational motion is first encoded in area Vl and then in area MT by direction-sensitive cells. Higher areas (MSTd) show selectivity for more complex forms of pattern movement, such as radial or spiral motion (Tanaka & Saito, 1989; Duffy & Wurtz, 1991; Orban *et al.*, 1992; Graziano *et al.*, 1994). Psychophysical studies also support the hierarchical arrangement of motion detection mechanisms (Morrone *et al.*, 1995). The local motions in rotating and expanding images are combined by specialized higher level mechanisms that integrate across large spatial scales (Freeman & Harris, 1992). Regan & Beverly (1978) argued that expansion is encoded independently of contraction, suggesting separate mechanisms may exist for each class of global motion. Several papers have reported illusions in perceived speed involving complex motion stimuli. In a direction-discrimination task Beardsley and Vaina (2005) observed a radial motion bias and preference for speed gradients. A radial speed gradient in a random dot pattern occurs when dot speed increases with distance from the stimulus center, which represent forward self-motion. Geesaman and Qian (1996, 1998) found that an expanding pattern appears to move faster than corresponding rotations and translations. Bex and colleagues found that the speed of radial gratings relative to translational gratings is overestimated by 20–60% (Bex and Makous, 1997; Bex, Metha & Makous, 1998). The results demonstrate that perceived speed depends upon the global pattern of motion. Bex and Makous observed that radial motion stimuli appear to move in depth relative to the observer. Expanding stimuli are typically perceived as approaching the observer. The speed of the perceived motion of the stimulus through three-dimensional space would then depend on the degree of perceived *motion-in-depth* as well as the actual speed of the stimulus in the plane of the display (Clifford, Beardsley & Vaina, 1999). Previous psychophysical studies have found evidence for the existence of specialized detectors sensitive to radial, rotational, and translational motion (Regan & Beverley, 1983; Freeman & Harris, 1992; Morrone, Burr & Vaina, 1995; Snowden & Milne, 1996, 1997). The results of these and other experiments suggest that these specialized detectors integrate local motions to obtain a global motion percept (Watamaniuk & Sekuler, 1992; Smith, Snowden & Milne, 1994; Morrone et al., 1995).

1.3. Motion perception in Virtual Environments

Experimental investigations of visual self-motion perception have benefited tremendously from the availability of specialized 3D graphics workstations that can simulate movement through virtual environments in real time. In this section we provide a short description of the technology and its advantages for research purposes, and an overview of the researches on motion perception that employed virtual environments.

1.3.1. Virtual environments as a research tool

The development of computer technology, 3-D graphics and visualization systems has lead to the realization of complex artifacts that blur the distinction between reality and its representation (Ellis, 1995). This technology makes use of digitally controlled displays that stimulate the human sensory organs, simulating the natural world as it is experienced by a human observer. These artificial interfaces are the so called *Virtual Environments* (VE). VEs are computer-based representations of a space where users can freely move their viewpoint and experience the space in real time. VEs have many potential applications, including education and training, design and prototyping, entertainment, rehabilitation, visualization, product design, therapy, tele-operations, as well as gaming. For the history of IVEs, see Ellis (1995), Kalawsky (1993), and Rheingold (1991).

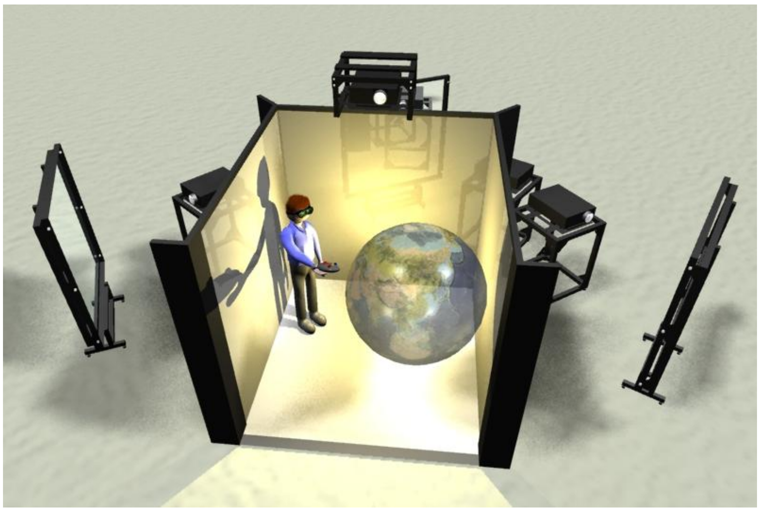

Figure 1.9: (from http://www.es.jamstec.go.jp/esc/research/Perception/cave.ja.html) an example of CAVE virtual environment.

A standard implementation of VE consists of placing multiple projection screens and loudspeakers around the user. Some of the first panoramic projection displays include the Cave Automatic Virtual Environments (CAVE™) in which the four walls (and sometimes floor) of a small, square room are back-projected with an image of the visual scene (Cruz-Neira, Sandin, & DeFantini, 1993), as shown in Figure 1.9.

A more recent and sophisticated type of panoramic projection consists of large curved projection screens, where the different images are blended together and the geometry of the virtual projection plane is warped to match the physical geometry of the projection surface. As an example, the *Panolab* installation at the Max Planck Institute for Biological Cybernetics can be seen in Figure 1.10.

Another common implementation of a VE involves the use of a head-mounted display (HMD), used in conjunction with a computer and a head tracker (Barfield & Furness, 1995; Biocca & Delaney, 1995; Durlach & Mavor, 1995; Kalawsky, 1993).

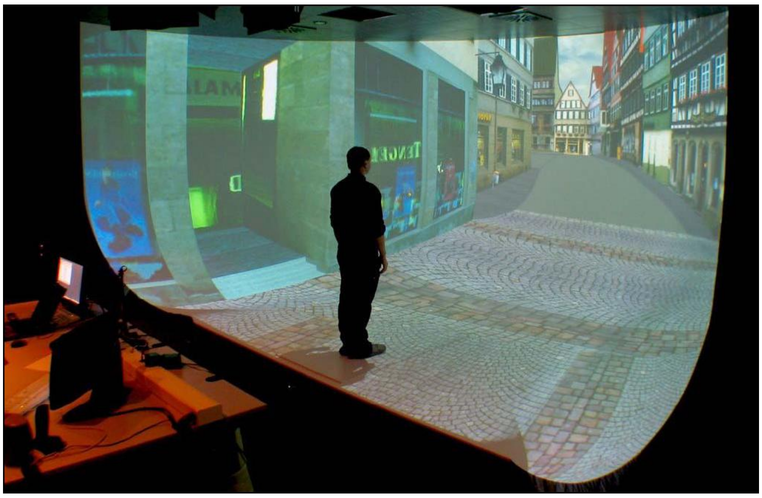

Figure 1.10: Spherical screen installed at the Max Planck Institute for Biological Cybernetics. It consists of four projectors which project onto a semi-spherical screen. Image warping for geometry correction as well as edge blending is done by openWARP® technology. www.openwarp.com.

Research requires a strict experimental control above the variables investigated but, on the other side, ecological validity is also an issue pursued by experimenters. Traditionally, psychology experimenters have created controlled and contrived situations in sterile laboratories, and employed specialized measurement devices, to the detriment of ecological validity. Advances in computer technology have allowed researchers to decrease the degree of tradeoff between control and validity (Figure 1.11). Virtual environments technology, by virtue of their being nearly optimal interfaces for the human senses, have the potential for maximally expanding the operating characteristic, thereby providing both high ecological validity and experimental control. Such a change in the operating characteristic afforded by VE technology will very likely increase the possibility to generalize experimental findings. In addition, VE technology will increase also the power of experimental research, because of the increases in experimental realism (Loomis *et al*., 1999).

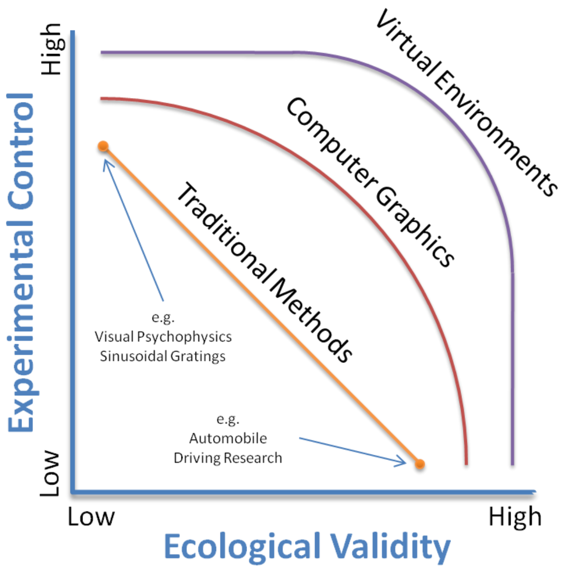

Figure 1.11: (adapted from Loomis, 1999) Experimentation in psychology implies a trade-off between experimental control and ecological validity. Virtual Environments enhance both.

One of the main advantage of VE is that such a technology allows researchers to separate and manipulate variables that in real life are coupled and, therefore, impossible, or nearly so, to disentangle (e.g. speed of forward translation and rate of expansion of the objects in the environment). Thus, in a driving study, one can selectively alter aspects of the road ahead to determine how much of the forward field-of-view influences the driver's behavior. Above all, VE users can experience situations without the expense or the risk that the same situations would bring in the real world.

1.3.2. Speed of self-motion in virtual environments

The availability of VE technology and specialized hardware to simulate motion through the environment in real time has brought tremendous advantages to the investigation of visual self-motion. Regarding the perception of visual motion, one of the topics that mostly have benefited from the VE technology is the theme of perceived speed during self-motion. Here we present a short collection of related studies.

Prokop, Shubert and Berger (1997) have investigated the effect of the optic-flow pattern on human locomotion. In subjects walking on a treadmill while looking at a virtual tunnel presented on a half-spherical screen they varied the velocity of the optic-flow. They found that visual information about self-speed leads to an unintentional modulation of the walking speed by affecting the stride length. Other authors (Flückiger & Baumberger, 1988; Baumberger, Flückiger & Martin, 2000) replicated the same results with a setup where the participants had to walk along a corridor in which the floor and the walls were projecting an optic-flow pattern at different velocities. More recently it has been observed that geometrically correct optic-flow appears to be too slow during simulated locomotion on a treadmill (Durgin *et al.*, 2005). It has been hypothesized that the lamellar flow is necessary for accurate speed perception, and that a limited field-of-view impedes the access to this cue during straight-ahead gaze.

Although it is not yet clear whether the same strategies used for natural locomotion apply to driving situations, where displacements occur in a higher speeds domain, it seems that results concerning subjective speed perception in full scale driving simulators are transferable to real road conditions. In fact, in a study carried out in a dynamic driving simulator with a large field-of-view (Panerai, 2001) the subjective speed perception in the absence of dashboard information was investigated. The results obtained turned out to be highly correlated to the subjective speed in real driving. In fact, the information input to the driver is predominantly visual (Evans, 1991) and, in a driving simulator, optic flow resulting from the continuous movement of the textured images of the scene is veridically displayed. Therefore, we found that a driving simulation offers a valid setup for the investigation of the speed of self-motion. A driving simulator is then a system providing a coherent multi-sensory environment for a driver to perceive real time changes and control a virtual vehicle (Kemeny & Panerai, 2003). The driver sits in a cockpit and activates commands. These determine the simulated vehicle motion on the basis of a vehicle dynamic model.

Many studies have been carried out in order to understand how drivers perceive the driving speed and which factors influence the driving behavior (Denton, 1980; Evans, 1991; Conchillo, Recarte & Nunes, 1997). Some studies have shown that the visually perceived speed during forward motion can be altered by the global optic flow rate and the discontinuity rate, the eye height (Flach, Junaid & Warren, 2004), and the expanding flow field (Girone & Durgin, 2004). It has been shown that the driver's perceived speed can be affected also by a limited field-of-view (Osaka, 1988). Another visual cue, the declination angle – the vertical angle between the horizon and the gaze direction – was recently shown to be a strong determinant of perceived distance and speed (Panerai, 2001). For example, varying the simulated eye-height in a task where a lorry driver had to maintain a safe distance with respect to a leading car vehicle, it was observed that by increasing the simulated eye-height, the corresponding perceived distance was also increased. Moreover, for the same increment in the simulated eye-height, higher driving speeds were observed, suggesting a reduced subjective speed perception. Specifically, as eye-height increases (i.e. farther removed from the ground), the magnitude of optic flow decreases (Gibson, 1979). Rudin-Brown (2006) explicitly tested the implications of this effect by evaluating speed perception in a simulated driving task. Drivers were positioned at varying eye-heights. Two eye-heights were chosen to represent the height experienced in a tall vehicle such as an SUV and the height experience in a low-slung vehicle such as a sports car. The results of this task demonstrated that speed perceptions were reported as faster when evaluated from a low eye-height (reflected in slower driving speeds) and slower when evaluated from a high eye-height (reflected in faster driving speeds). The perception of driver's speed may depend also on the distance to objects on the side of the road (Fildes & Lee, 1993). Virtual environments offered the possibility to study other factors that have been found to affect the perceived speed during self-motion. Those factors are the spatial frequencies and the horizontal size of the field-of-view (Distler, Gegenfurtner, van Veen & Hawken, 2000).

1.3.3. The present study

The models of motion and speed perception presented so far are somehow limited to the analysis of relative simple motion patterns. They are mainly applicable for two-dimensional motion and they have been tested only with low-level psychophysical stimuli. None of those models make explicit predictions in term of perceived self-motion. In more natural situations the range of spatio-temporal frequencies, contrast levels and speeds are not only considerably extended, but also dynamically changing over time.

With the experiments of this thesis we want to explore how complex motion from three-dimensional environments can be accounted. We focused primarily on the effect of contrast reduction on the produced speed in a driving simulation. It has been argued that the effect of contrast on the perceived speed occurs also in real life when driving in low visibility conditions (Green, 1983; Anstis, 2003) or during the night (Gegenfurtner, Mayser & Sharpe, 1999). Some evidences have been provided that in a driving simulation the reduction of the contrast of the road surface induces a lower perceived speed (Distler & Bülthoff, 1996). In a highly cited experiment, Snowden, Stimpson and Ruddle (1998) have demonstrated that in a driving simulation with a uniform reduction of the contrast of the whole scene (fog) drivers perceived a lower speed and tended to speed up in order to reach a given target speed. In this dissertation, with a realistic simulated fog instead of a uniform contrast reduction, we demonstrated that the produced driving speed is decreased, as a consequence of a higher perceived speed.

Figure 1.12: A picture taken while driving in foggy conditions. The central region of the field-of-view is completely hidden by the fog and therefore the leading car is hardly visible. The peripheral areas of the image, depicting the more proximal regions, are still visible.

Our contrast reduction affected differently the distant and close regions of the environment as it usually happens in real situations (Figure 1.12). The explanation that we provided assumes that the fog reduces the visibility of the distant region of the scene (slow angular velocities) so that only the information from the periphery of the field-of-view (high angular velocities) is available. Therefore, the own speed estimate is biased towards higher values. This hypothesis was supported also by other behavioral studies where it has been shown that a restricted visual field decreases the self-rated perceived speed (Salvatore, 1968; Osaka, 1988).

Chapter 2

Perceived and produced speed with reduced image contrast

In this chapter we describe the experiments that we conducted to investigate how the contrast of the scene affects the produced and perceived speed of self-motion. In a driving simulation we tested whether a realistically simulated contrast reduction (fog) increases or decreases the produced speed (section 2.1). We demonstrated in a psychophysical experiment (section 2.2) that when the image contrast of a moving scene was gradually reduced, the speed was perceived as being lower than the speed of a reference scene with clear visibility. In a different setup provided with a more natural field-of-view and a simple vehicle mock-up we replicated the same results. The participants systematically overproduced the target speed when driving in foggy conditions (section 2.3). In a subsequent experiment (section 2.4) we addressed the question whether driving speed changes according to different fog densities. We found that the produced driving speed was lowered according to the amount of gradient contrast reduction but it remained unaffected by a uniform implementation of the contras reduction. In section 2.5 we present the results of further analyses computed on other performance measures, like lateral position and traveled distance, collected in the behavioral experiments. Finally we run a psychophysical experiment to demonstrate that the uniform contrast reduction has no effect on the perceived speed, independently of the visual areas of stimulation (section 2.6).

2.1. Fog decreases the produced speed

2.1.1. Introduction

In this behavioral experiment we implemented a driving scenario to test whether a realistically simulated contrast reduction of the visual image induces the same effect that has been measured by Snowden et al. (1998). In that highly-cited experiment (Snowden, Stimpson and Ruddle, 1998) participants were asked to drive at a given target speed in a driving simulation, and as the scene became foggier, subjects produced faster speeds. This speeding behaviour has been interpreted as a reaction to a perceived lower driving speed caused by the scene contrast reduction due to the presence of fog. In that study, fog was implemented by blending a partially transparent surface over the rendered scene. This method, however, leads to an unrealistic uniform contrast reduction, which does not simulate the real environmental conditions in fog (Dyre, Schaudt & Lew, 2005; Shrivastava, Hayhoe, Pelz & Mruczek, 2005). A more realistic account of fog conditions is a contrast reduction that depends on the distance of the objects to the observer. Recently, it has been found that an environment with exponential fog (where the contrast is exponentially reduced with distance), displaying a contrast gradient in depth instead of a uniform contrast reduction, leads to higher perceived speeds (Dyre *et al*., 2005). According to the authors of this psychophysical study, a contrast gradient in depth leaves visible only the proximal portion of the visual scene, which contains the higher motion signals, thus increasing the global optic flow rate and consequently the perceived speed. As a result, the global rate of optic flow indicates a higher driving speed and a driver intending to reach a particular target speed will rather produce a lower speed. The purpose of this experiment was to investigate the effect of a realistic (exponential) fog on speed production during an active driving task. As such we used the same experimental approach as Snowden et al. (1998), but were expecting opposite results given the prediction above.

2.1.2. *Method*

2.1.2.1. *Apparatus and stimuli*

The virtual environment was rear-projected at 60 Hz onto a flat 2.2 x 2 m screen with a resolution of 1280 x 1024 pixels (D-ILA projector, JVC DLA-C15) in an otherwise dark room. The projected scene covered a field-of-view of 75º x 70º from the viewing distance of 1.4 m. The Virtools software solutions and the VR Pack add-on allowed us to control the experiment and to distribute the scene rendering on a two-PC cluster. Participants operated the pedals and the steering wheel (Microsoft Sidewinder Forcefeedback Wheel) that was mounted on a desk. Pedal and steering wheel actions were received by a "master" computer (Windows XP), which updated position and orientation of the virtual car on basis of these inputs at a fixed frame-rate of 60 Hz. The updated values were sent to a "slave" computer to render and display the visual scene (Figure 2.1).

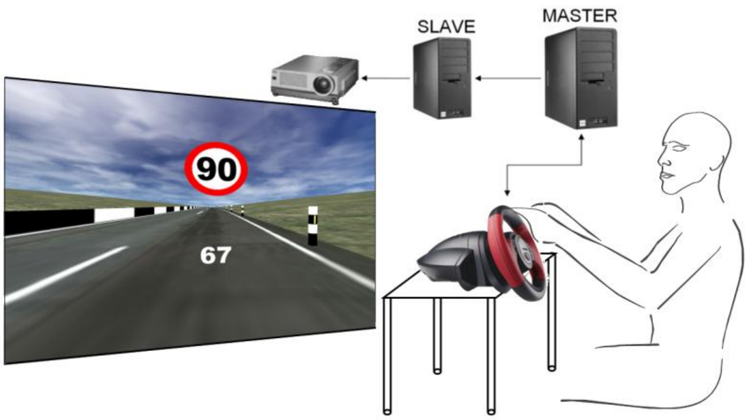

Figure 2.1: An overview of the experimental setup. A master computer records the signals from the input devices (pedals not shown) and updates the spatial coordinates of the driver's point of view; a slave computer renders the scene.

The Havok Game Dynamics SDK, embedded in the Virtools Physics Pack add-on, was used to setup and fine-tune the behaviour of the virtual car and the sensitivity to the driving devices.

The virtual environment consisted of a modelled section (8 km length) of a real local motorway, maintaining its geometry and course. Gentle curves and some height variations forced the driver to keep an active steering and speed control. The road had two lanes for each driving direction, separated by a traffic divider painted with large black-and-white stripes. Along the right side of the track, road poles were set every 50 meters. On both sides of the roadway a slanted plane covered with a grass texture simulated hill sides (figure 2.2a).

We consider here only the six experimental conditions deriving from the combination of the two factors *target speed* (40, 60 or 90 km/h), and *visibility* ('clear' vs. 'foggy' environment with gradually reduced contrast). The target speed was presented as a speed limit sign that appeared for five seconds at the beginning of each trial (see figure 2.1).

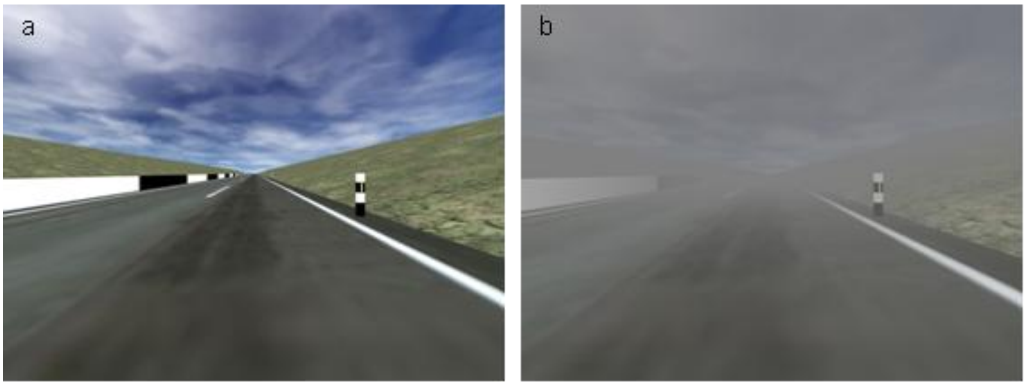

Figure 2.2: The environment as it appeared to the observers: (a) the "clear" condition with a contrast of 0.7 (RMS_C; see text for details) and (b) the "foggy" condition with a contrast reduced to 0.3.

To obtain a realistic contrast reduction we created a real-looking fog in the environment according to an exponential model (exponent $\lambda = -0.17$): the fog became denser as the distance to the observer increased (figure 2.2b). At a distance of 27 m from the observer the visibility dropped down to zero. As suggested by Moulden, Kingdom and Gatley (1990), we quantified contrast of the scene as the normalized root mean square (C_{RMS}) of the luminance values of the displayed environment (i.e. ratio of standard deviation to mean of luminance values). The RGB pixel values of the scene were converted into their corresponding grey level values and their luminance distribution was determined based on the empirically determined function between luminance and grey values. Five snapshots were taken at random positions along the road to determine the average contrast. The C_{RMS} for the clear and the foggy condition was 0.7 and 0.3, respectively. The luminance of the scene ranged between 3 and 33 cd/m^2.

2.1.2.2. Participants

Nine subjects (4 females and 5 males) with normal or corrected-to-normal vision participated in the study. All participants had a valid driving license for at least five years and were considered as experienced drivers since they declared an everyday car usage. They were paid and were naïve as to the purpose of the experiment.

2.1.2.3. Design and procedure

In the training phase participants learned to reproduce the target speeds required during the main experiment. No environmental manipulations were implemented, but a recurring digital tachometer, appearing at the center of the screen, provided the instantaneous driving speed for four seconds every ten seconds. With the tachometer being visible, the observer could compare and adjust the driving speed, whereas, when the tachometer was hidden, he/she was forced to look at the environmental optic flow and learn the relationship with the current driving speed. The three target speeds were presented five times, for an overall number of fifteen trials, each of which lasted one minute.

During the main experiment, the drivers' behaviour was tested under 6 randomly interleaved conditions (3 target speeds x 2 visibility conditions) in a within-subject design (intermixed with sessions from additional conditions reported in section 3.). At the beginning of each trial, a speed limit sign appeared for five seconds in the middle of the scene indicating the required target speed. Participants were instructed to accelerate up to the indicated target speed, to keep it for five seconds and to terminate the trial by a button press. Feedback about the instantaneous speed was not provided anymore. The average speed produced during the last five seconds of each trial was considered as the produced speed for the statistical analysis.

2.1.3. Results

We conducted a repeated-measures analysis of variance (ANOVA) and found a significant main effect of each of the independent variables. The significant effect of the target speed ($F(2,16) = 84.79$, $p < .001$) indicates that people correctly executed the task and were able to discriminate between the three different driving speeds (the average produced speed was 54.6 km/h, 81.0 km/h, 110.1 km/h in the 40, 60 and 90 km/h conditions, respectively). Figure 2.3 illustrates the general overproduction of the driving speed of 18.6 km/h (31.3%). The overestimation effect was significant ($t(8) = 3.99$, $p < .01$) and proportional to the target speeds. In fact, the normalised values of the produced speed did not differ over the three target speeds ($F(2,24) < 1$, $p = .52$). This result is consistent with the known phenomenon of speed underestimation in driving (Recarte and Nunes, 1996). Actually, the general speed overproduction can be interpreted as driver's compensation to the underestimation of speed.

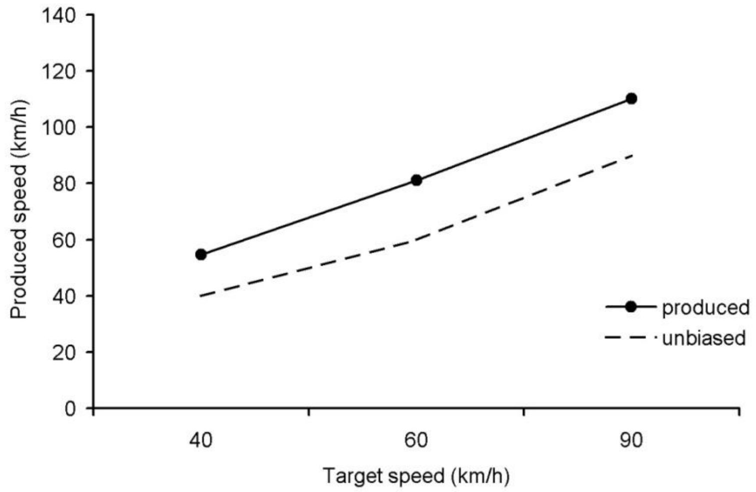

Figure 2.3: Main effect of the “target speed” factor and general speed overproduction. Dashed line indicates the correct speed.

We observed also a significant main effect of the visibility factor ($F(1,8) = 38.05$, $p < .001$), i.e. the produced speed in the “foggy“ conditions was lower (-8%) compared to the “clear“ conditions (figure 2.4). There was also a significant interaction between the target speed and the visibility factor ($F(2,16) = 6.1$, $p < .05$). A post-hoc comparison using Newman-Keuls test showed that at the lowest target speed of 40 km/h the difference between the clear and the foggy environment was not significant. No other high-order interactions proved to be significant.

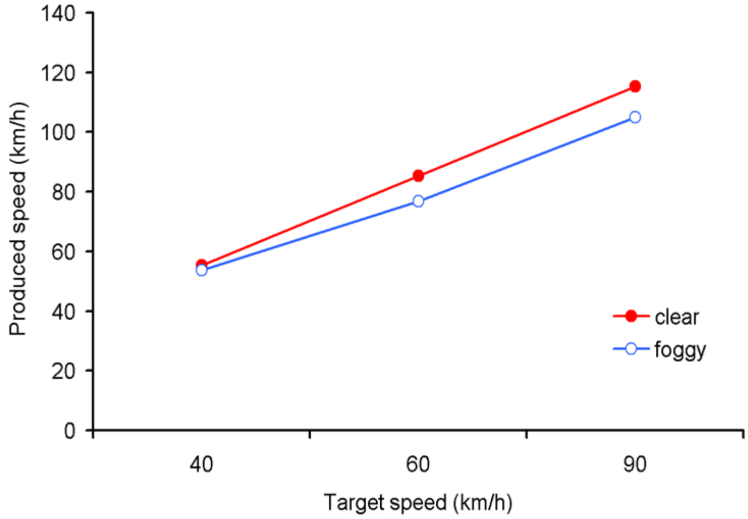

Figure 2.4: Effects of the "visibility" factor. Drivers slowed down in a foggy environment unless they were driving at the slowest required speed of 40 km/h.

2.1.4. Conclusions

The main result of the experiment is that in our realistic driving scenario the presence of fog led to lower speeds, and not to speeding. This result is in accordance with and extends previous psychophysical finding (Dyre *et al.*, 2005), and supports the interpretation that fog masks distal portions of the scene, leaving only the proximal parts with higher angular velocities visible. As a result, the global rate of optic flow will indicate a higher speed (Watamaniuk and Duchon, 1992) and a driver intending to reach a particular target speed will level off at a lower speed.

2.2. Fog increases the perceived speed

2.2.1. Introduction

We run a second experiment in order to compare the behavioural results on produced speed caused by the contrast reduction to psychophysical estimates of perceived speed under the same environmental conditions. In the psychophysical study we could also directly compare speed perception under gradually and uniformly reduced contrast conditions while with equal amount of contrast reduction. Moreover, using a psychophysical two-interval forced-choice task (2IFC) with an adaptive staircase procedure (Levitt, 1971) instead of a driving task, we could avoid the potential interference of cognitive strategies (e.g. safety considerations induce drivers to slow down) that might have been used when driving in fog.

2.2.2. Method

We conducted a psychophysical study in order to determine the subjective perceived speed (Point of Subjective Equality: PSE) while driving through two types of contrast reduction as compared to clear conditions.

2.2.2.1. Apparatus and stimuli

The apparatus was the same as in the previous experiment, except for the input devices, that were substituted by a standard keyboard to provide the answer at every trial.

Since in this experiment the observers had to execute a passive task, instead of an active driving task, we presented a straight piece of road, displaying the same visual features as in the previous experiment, instead of an entire real road track. We kept then the same textures, the geometry of the road and the side hills, the traffic divider and the road poles.

The *clear* and *exponential* visibility conditions were the same as in the previous experiment and had the same contrast (C_{RMS}) values of 0.7 and 0.3, respectively. In this experiment we implemented also a *uniform* contrast reduction all over the scene adding a semi-transparent gray surface between the virtual observer in the scene and the environment. We adjusted the transparency value (*alpha*) of the new layer in order to match the reduced contrast value obtained with the exponential fog in the previous experiment. The procedure to compute the RMSC was the same as used in the behavioural experiment.

2.2.2.2. Participants

Eight subjects (4 females and 4 males) with normal or corrected-to-normal vision were recruited. They were paid and were naïve as to the purpose of the experiment.

2.2.2.3. Design and procedure

The experimental manipulations included 3 target speeds (40, 60, and 90 km/h) of the standard stimulus, and 3 visibility conditions of the environment (*clear* without any manipulations, *uniform* with uniformly reduced contrast and *exponential* with realistic exponential fog). For each target speed the three visibility conditions were compared in a within factor design (3 x 3). We used an adaptive staircase procedure (1 down, 1 up), as suggested by Levitt (1971), with a two-interval forced-choice task (2IFC), where the subjects had to decide which of two sequences displayed the forward motion with a higher speed. At every trial, two sequences of forward motion, appearing as passive driving, were shown for two second each, interleaved by a black screen for one second (figure 2.5).

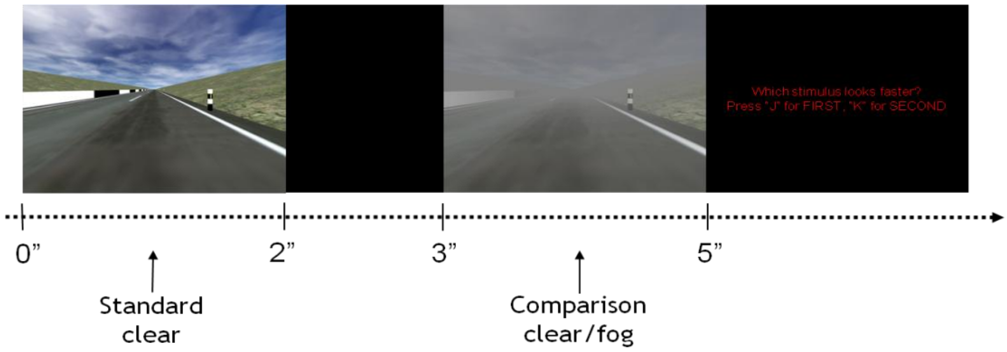

Figure 2.5: Typical time-course of a trial. The overall presentation time for the two scenes was 5 seconds, after that the observer could choose which stimulus appeared as moving faster.

The *clear* scene was always the reference stimulus, and it could scroll at one of the three target speeds. The comparison stimulus was one out of three possible visibility conditions. After each trial, the subject was asked to indicate the faster sequence and start the following trial by button press. The starting value of the comparison speed was set at +/- 50% of the standard, and the step size was 5% of the standard. There were both ascending and descending series of the staircase for each target speed and visibility condition. The series were randomly interleaved. The order of standard and comparison was balanced across trials. For each subject, a series was terminated after 12 reversals. The values of the last 10 reversals where used to compute the proportions of times that the comparison stimulus was considered as being faster. We computed also the psychometric function and the *Point of Subjective Equality* (PSE) for each speed and visibility condition (figure 2.6).

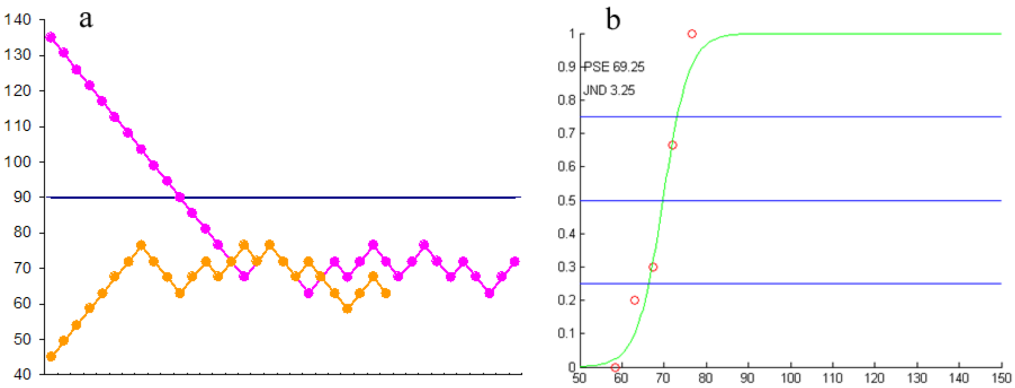

Figure 2.6: Example of a trial course with the related psychometric function. A sequence with interleaved ascending (orange) and descending (purple) series for the condition with reference speed = 90 km/h (the blue horizontal line) and visibility = exponential (a). In green, the corresponding psychometric function (b). Note that the value of the PSE is lower than the reference stimulus.

The fitting of the psychometric function was done by the following exponential function:

$$y = 1 - \frac{1}{e^{b(x-a)}+1} \qquad (2.1)$$

where b is the slope of the function, a is the intercept and x is the value of the comparison stimulus.

2.2.3. *Results*

We conducted an analysis of variance for repeated-measures (ANOVA) on the PSEs, and found a significant main effect of the target speed ($F(2,14) = 1313.6$, $p < .001$) and the visibility condition ($F(2,14) = 18.19$, $p < .001$). We obtained also a significant interaction (see figure 2.7) between the two factors ($F(4,28) = 5.81$, $p < .05$).

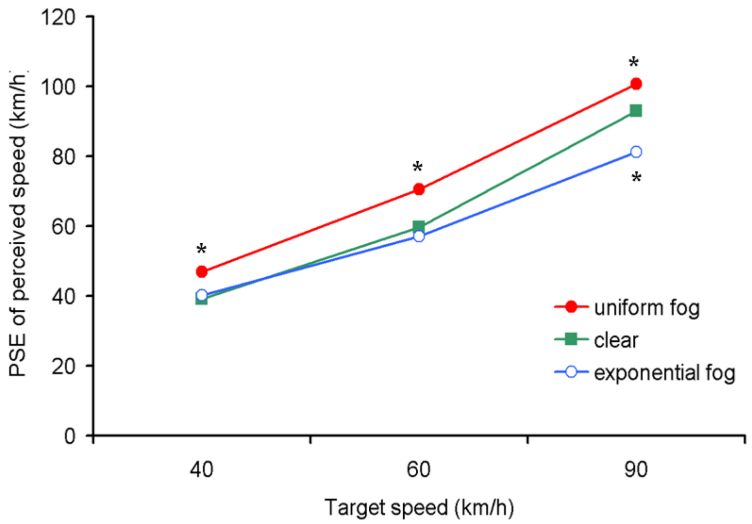

Figure 2.7: Effect of the interaction between the "target speed" and the "visibility" factors. Speed appeared slower with a uniform fog (higher PSEs). In an exponential fog, driving speed was overestimated at the highest speed of 90 km/h (lower PSE).

In the "uniform" fog condition the PSEs of the perceived speed are, on average, 8 km/h (15%) above the "clear" condition speed. In the "exponential" fog condition the PSEs are, on average, 5.7 km/h (-5%) below the "clear" condition speed. A post-hoc comparison (Newman Kleus) yielded a significant difference only at the highest speed (90 km/h).

2.2.4. Conclusions

The main result of the first experiment is that in our realistic driving scenario the presence of fog led to lower speeds, and not to speeding (Snowden *et al.*, 1998). This result is in accordance with our previous behavioural experiment and the psychophysical findings from Dyre, Schaudt and Lew (2005). With the second experiment we have confirmed that in realistic foggy conditions the speed is indeed perceived as being faster than the actual speed. Interestingly, this fog effect was observed only for speed 90 km/h, but not at the lower target speeds of 60 and 40 km/h. This result is then in good agreement with the finding that drivers slowed down only at the higher speeds. Furthermore, this psychophysical result rules out more cognitive explanation of the speed reduction in fog (e.g. reaction due to safety considerations). Finally, we have observed that with uniform, unrealistic, contrast reduction speed is indeed underestimated, consistently with previous results (Snowden *et al.*, 1998). We conclude that driving in fog provokes people to adjust their speed, but to lower, not higher, velocities - an effect which has a rather perceptual origin. Further discussion about the present results is presented in Chapter 4.

2.3. Fog decreases the driving speed also in a realistic driving scenario

2.3.1. Introduction

We developed a third experiment in order to compare directly at the behavioral level the effects of the two types of contrast reduction tested previously in the psychophysical task (see section 2.2). In this study we wanted also to provide more ecological validity to the results and for this purpose we used a different setup. We tested the behavior of drivers under clear and reduced visibility conditions while driving in a virtual environment with natural field-of-view (FOV) using the *Panolab* facilities of the Max Planck Institute for Biological Cybernetics.

2.3.2. Method

2.3.2.1. Apparatus and stimuli

The experimental setup consisted of a large (7m) semi-spherical projection system that includes three vertical screens and floor projection (Figures 1.10, 2.8).

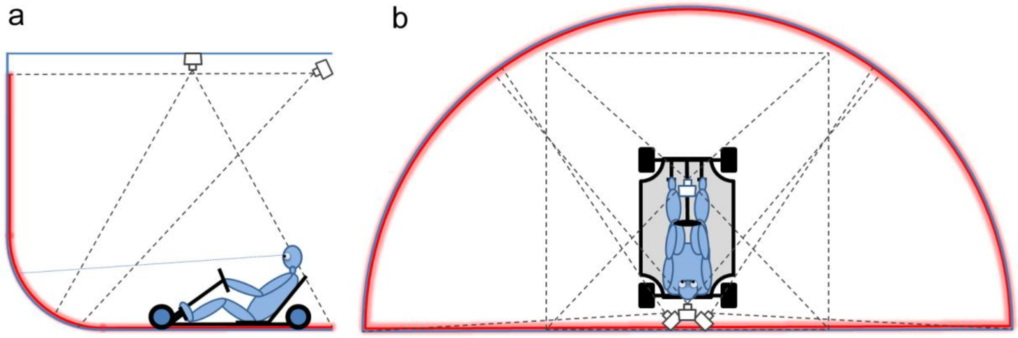

Figure 2.8: Lateral (a) and top (b) view of a schematic representation of the experimental setup. Dashed lines indicate the cones of projection of the four beamers. Glowing lines indicate the resulting extent of the projection surface.

This projection system wraps around the observer to provide an image that embraces almost the entire visual field (see Figure 2.9 for a comparison of the typical FOV of different screen types compared to the human FOV).

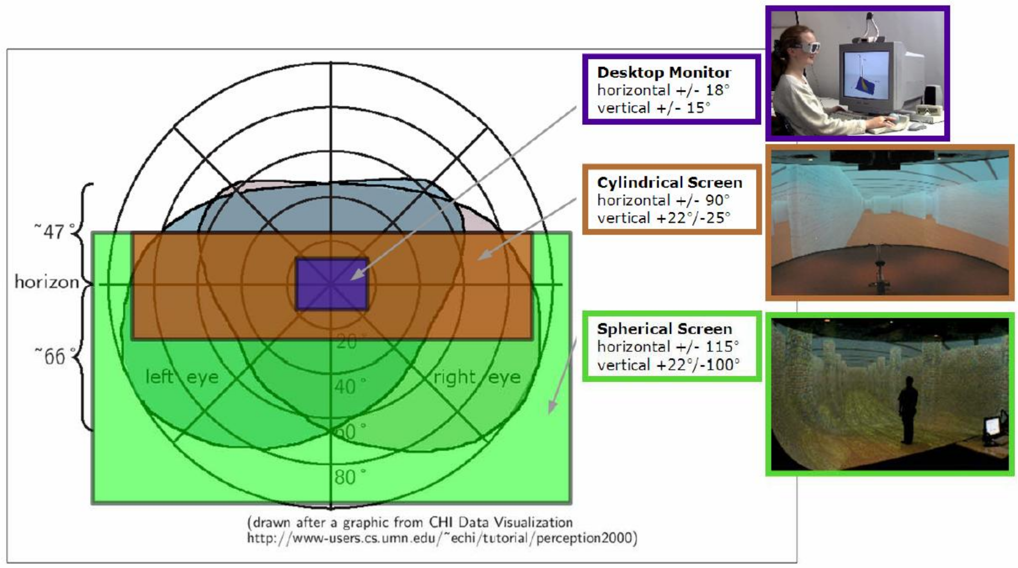

Figure 2.9: FOV comparison. The spherical plot shows the extent of the human FOV for both the right eye and the left eye. The overlaid boxes show the FOV for several display systems. The spherical projection screen covers a much larger extent of the human field-of-view.

The scene was displayed at 60Hz by four LCD-projectors with a resolution of 1400×1050 pixels each. Overlapping regions were blended by openWARP® technology. The geometry correction of the projected scene was adjusted for an eye height of 0.8m at a distance of 3m from the screen. A simplified vehicle mock-up equipped with steering wheel and pedals served as driving interface. In figure 2.10 the functioning of the accelerator pedal is described in details, since the system was differently implemented from the previous experiment, in order to provide a more direct control of speed and acceleration.

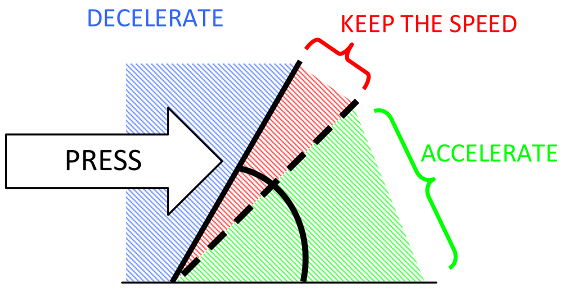

Figure 2.10: The accelerator pedal. To increase the speed the accelerator pedal had to be pressed within the green region indicated above (the higher the pressure and the faster the acceleration). To keep a constant speed the pedal had to be released back to the red region. To reduce the speed it had to be completely released.

The virtual environment consisted of a model of a local dual-carriageway road with two lanes in each direction. The road path had several curves with different radius (ranging from 250 to 7500 meters) and ascending and descending sections. A traffic divider on the left side separated the two carriageways and road poles on the right side were placed every 50 meters. Road markings on the textured road surface delineated the traffic lanes (figure 2.11).

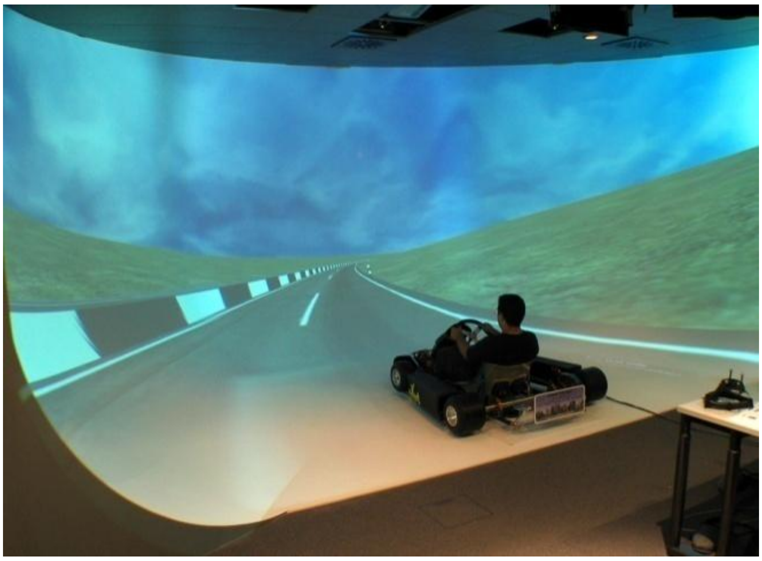

Figure 2.11: The experimental setup with the virtual environment displayed on the screen as it appeared during the experiment.

In this highly realistic driving scenario we tested a combination of two experimental factors: the *target speed* (40, 60 and 90 km/h) and the *visibility* (clear, gradually reduced and uniformly reduced). The target speeds appeared as speed limit signs in the middle of the screen at the beginning of each trial. In the condition with gradual contrast reduction the visibility of the scene was reduced exponentially as a function of the distance from the observer. This condition was implemented by adding an exponential fog in the virtual scene, according to the fog model:

$$C_r = C_f\,(1-\beta) + C_o\beta, \tag{2.2}$$

where

$$\beta = e^{-fd} \tag{2.3}$$

and C_r is the resulting color, C_o is the original color of the object displayed in that pixel, C_f is the color of the fog, f is the density of the fog, and d is the linear distance of the object displayed in that pixel. We decided to set the fog density to 0.1, in a range from 0 (no fog) to 1 (no visibility). This value allows a visibility range of 30 meters, according to the *meteorological visibility range* (MVR) that indicates at which distance a white object appears with 5% contrast (Koschmieder, 1924).

The uniformly reduced contrast condition was implemented by inserting a transparent virtual plane in front of the scene. The plane color was composited with the color of the background image, according to a standard color transparency model (RGB-alpha):

$$C_r = C_p \alpha + C_o (1 - \alpha), \quad (2.4)$$

where C_r is the resulting color, C_p is the color of transparent plane, C_o is the original color of the object displayed in that pixel, and α is the alpha value of the pixel in the transparent plane.

The transparency of the plane was adjusted in order to obtain the same amount of contrast as computed in the corresponding fog condition and the opacity (1 – transparency) was then set to 0.4 (in a range where 0 indicates full transparency and 1 full opacity). As suggested by Moulden, Kingdom and Gatley (1990), we quantified the contrast of the scene as the normalized root mean square (C_{RMS}: the ratio of standard deviation to mean) of the luminance values of the pixels in the displayed environment. The colour of each pixel was converted into the corresponding brightness (a gray-scale, achromatic value in the RGB colour system) and the scene luminance distribution was computed based on the empirically determined function between luminance and brightness. The computed values were 0.86 for the clear visibility and 0.47 for the reduced visibility.

The color of both the fog and the plane was set to a medium gray level (RGB = [128,128,128]), which represents the frequently experienced fog color due to light absorption and Mei scattering in the atmosphere.

In order to prevent drivers from decelerating because of unexpected curves, the white road-edge lines were always unaffected by the fog and fully visible at any distance.

2.3.2.2. Participants

We recruited 20 expert drivers, who were paid and naïve as to the purpose of the study. They declared to drive at least twice a week and to own a driving license for at least five years. All participants had normal or corrected-to-normal vision.

2.3.2.3. Design and procedure

The experimental conditions consisted of the combination of the experimental factors *target speed* and *visibility* in a within-subject design, randomly repeated in five subsequent blocks for an overall number of 45 trials (3 × 3 × 5). The duration of the experiment was about 2 hours, with the possibility for the participants to take a break after each block of trials.

A training session was necessary in order to get the participant familiarize with the driving interface and the experimental task. During this session the participants' task was to learn how to drive at a required speed. More specifically they had to adjust the driving speed in order to match the indicated target speeds (the same of the experimental session). In each trial, a digital tachometer indicating the instantaneous speed was displayed in front of the driver and served as visual feedback of the current speed. The tachometer was visible every time and as long as the current speed was not matching the target speed. When the tachometer disappeared the participants had to keep that speed for one minute and to pay attention to the environment. They were explicitly instructed to look at how fast the scene was flowing when driving at the correct speed. They were told that they had to learn how to reach the required speed looking at the environment, because in the experimental phase a feedback of the current speed was not provided anymore. After one minute driving at the correct speed (i.e. without numerical speed feedback) the following trial was loaded. With this procedure each participant could develop the right sensitivity for the pedals and was exposed to the correct target speed for the same presentation time. Each of the three target speeds was repeated five times in random order. The duration of the training was less than 20 minutes.

In the experimental phase participants were asked to drive on the right lane of the road, reach the indicated target speed (which appeared as a speed limit sign for four seconds at the beginning of each trial), keep it for five seconds, and terminate every trial by pressing a button. To fulfill the requirements the participants had to remember what they had learned during the training and look at the environment to produce the correct speed. The average speed produced during the last five seconds of each trial was considered as the produced speed for the following statistical analyses.

2.3.3. Results

Five participants had to be excluded from data analysis because they reached the maximum speed more than once. We established this rule to avoid considering participants who show ceiling effect and unreliable performance. In fact, the maximum speed was set to 150 km/h, well far from the highest target speed of 90 km/h.

We conducted an analysis of variance for repeated measures (ANOVA) and found a main effect of the target speed ($F(2,28) = 114.76$, $p < .001$), as shown in Figure 2.12. The three target speeds were slightly overproduced (on average 8%). This indicates that in the current experimental setup the amount of speed overproduction was significantly reduced in comparison to the results of the first experiment. The significant difference between the produced speeds indicates that the participants could drive consistently with three target speeds.

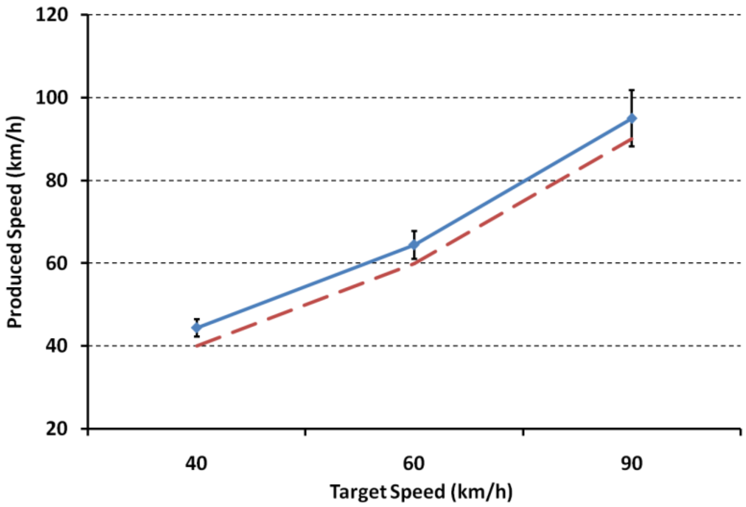

Figure 2.12: Produced speed as a function of the target speed and general speed overproduction. Dashed line indicates the correct speed.

The main effect of the visibility ($F(2,28) = 8.52$, $p < .005$) is shown in Fig. 2.13.

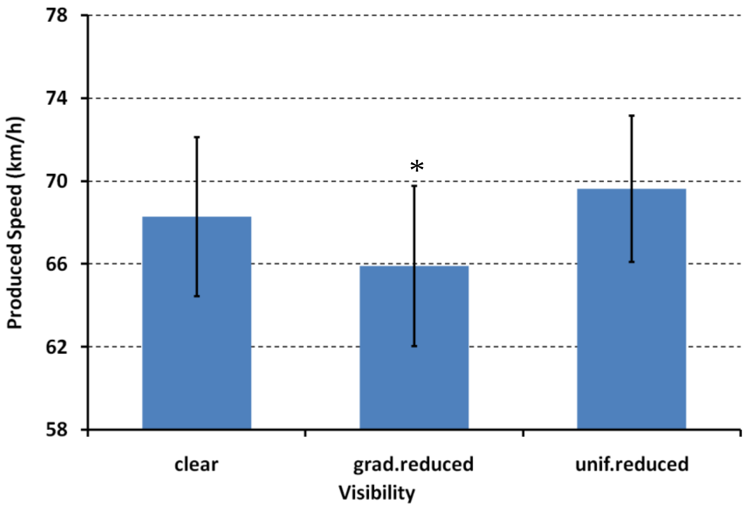

Figure 2.13: Produced speed as a function of the visibility condition.

A post-hoc test for multiple comparisons (Bonferroni) revealed that only the produced speed in gradually reduced contrast condition was significantly lower than the other two. The interaction effect between the target speed and the visibility was also significant ($F(4,56) = 3.31$, $p < .05$), as shown in Figure 2.14. The participants produced significant lower speed while driving in the gradient contrast reduction condition at the highest target speed, whereas the produced speed held steady in all the uniformly reduced visibility conditions.

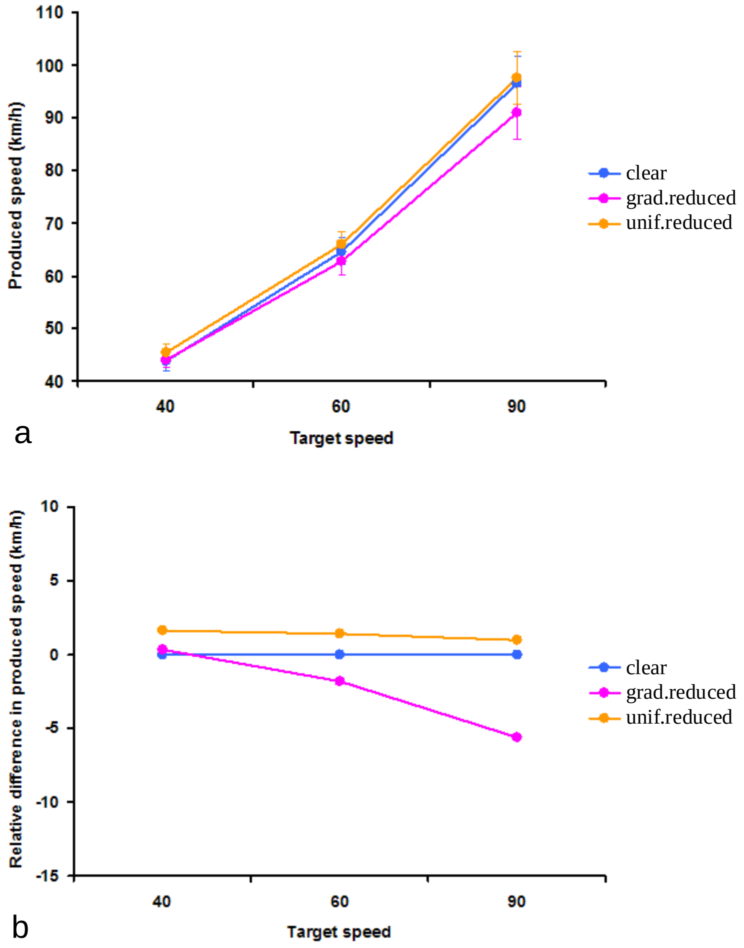

Figure 2.14: Produced speed as a function of target speed and visibility condition (a). The same data are plotted to visually enhance the differences (b).

2.3.4. *Conclusions*

These results confirmed the speed underproduction measured in the first experiment in the foggy condition even in large FOV environments. Further discussions are presented in Chapter 4.

Special attention seems necessary when simulating fog conditions. Indeed, we showed that the way fog is rendered in virtual environments dramatically changes the drivers' behavior and performance. A realistic implementation of a contrast attenuation function masks the field-of-view in a sensible way, and consequently biases the perceived driving speed and the driving behavior. On the other hand, we can adapt with relative ease to a uniform contrast attenuation, which corresponds rather to a "dirty windshield" situation (Figure 2.15 and for comparison Figure 1.12).

Figure 2.15: A dirty windshield and the uniformly induced contrast reduction

2.4. Produced speed is independent of uniform contrast reduction

2.4.1. Introduction

The results of the previous experiment did not confirm the effect of speed overproduction in the uniform contrast reduction conditions, as we were expecting from the psychophysical results of the second experiment. A possible reason for this could be that the contrast was not decreased to a sufficient level in order to elicit the expected effect. In fact, in the first experiment the reduction was approximately 58%, while in the third it was limited to 45%. Thus, we decided to run a control experiment in which we varied systematically the amount of contrast reduction from clear visibility (C_{RMS} = 0.86) to very low image contrast (C_{RMS} = 0.16), corresponding to an overall reduction of about 80%.

2.4.2. Method

2.4.2.1. Apparatus and stimuli

The physical setup, the driving interface and the virtual environment were the same as in the previous experiment, but only one speed of 90 km/h was set as target speed.

The experimental factors were the *type* of contrast reduction (gradient or uniform) and the *amount* of contrast reduction (no reduction, low, medium and high). Figure 2.16 shows how the colors of the original scene were affected by gradient and uniform contrast reduction, according to the fog model and the compositing model described in the paragraph 2.3.2.1.

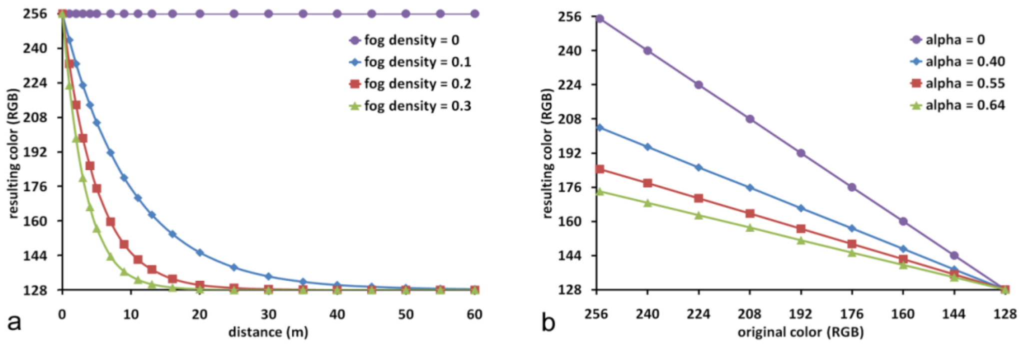

Figure 2.16: Effects on the image colors in the gradient and uniform contrast reduction. In the foggy conditions, a white pixel reduces its brightness, approaching the fog color (gray), as a function of its distance from the observer. The density of the fog affects the steepness of the curve and the distance at which the color of the scene become undistinguishable from the fog color (a). In the uniform contrast reduction, an increase in the opacity (alpha) of the transparent plane causes a compression of the original pixel color toward the plane color (b).

We varied the amount of fog thickness in order to create four scenes where the visibility ranged from clear to very low, according to the *meteorological visibility range* (MVR) (Koschmieder, 1924), as shown in table 2.1. In the uniformly reduced contrast conditions, the transparency of the plane was adjusted in order to obtain the same amount of contrast as computed in the corresponding fog conditions. The normalized root mean square (C_{RMS}) of the luminance values (Moulden, Klingdom & Gatley, 1990) was used as a measure of the image contrast level.

In table 2.1 the combination of values of the experimental conditions is shown, together with the corresponding measured contrast.

In order to prevent drivers from decelerating because of unexpected curves, the white road-edge lines were always unaffected by the fog and fully visible at any distance.

		Amount of contrast reduction			
		No	Low	Medium	High
Type of contrast reduction	Gradient (fog density)	0	0.10	0.20	0.30
	Uniform (plane opacity)	0	0.40	0.55	0.64
Measured contrast	C_{RMS}	0.86	0.47	0.25	0.16
	%	100	55	29	19
MVR	meters	∞	30	15	10

Table 2.1: Experimental conditions and contrast levels. For each type and amount of contrast reduction the corresponding values of the manipulated parameters (fog density and plane opacity) are shown (note that opacity = 1 – transparency). The contrast is reported as both dimensionless number and percentage. The MVR indicates the visible distance of an object with 5% contrast.

2.4.2.2. Participants

We tested 17 participants between the ages of 21 and 25. They were naïve as to the purposes of the experiment, although they had been introduced to the topic of the research during a preliminary meeting. All participants had normal or corrected-to-normal vision.

2.4.2.3. Design and procedure

In a within-subject experimental design we asked the participants to drive in all the 8 visibility conditions (2 type of contrast reduction × 4 amount of contrast reduction) in 5 repeated blocks, for an overall number of 40 trials. The conditions were randomly interleaved within every block. The whole experiment lasted about one and a half hours.

A first training phase allowed the participant to familiarize with the task and the simulator. During this phase the participants were required to drive for ten minutes in clear visibility conditions at the target speed of 90 km/h. Every time and as long as the driving speed and the target speed were not matching, the current speed was being visualized on the screen. When the correct speed was produced the numerical feedback disappeared. Participants were instructed to learn how fast the scene looked like when driving at the right speed, in order to reproduce the same speed in the following phase. In the experimental phase participants were asked to drive on the right lane of the road, reach a target speed of 90 km/h, keep it for five seconds, and terminate every trial by pressing a button. The average speed produced during the last five seconds of each trial was considered as the produced speed for the following statistical analyses.

2.4.3. Results

We adopted the same rule as described in paragraph 2.3.3 to exclude from the statistical analyses three participants from the original pool and therefore the results refer to 14 participants.

We found that the average produced speed for all the participants was about 96.6 km/h. At the one-sample t-test this value resulted to be significantly higher than the target speed ($t13 = 2.43$, $p < .05$) with 7% of speed overproduction. Regarding the contrast manipulation, the recorded data *per se* do not allow to distinguish between the data collected in an unaffected contrast condition and the data from the conditions where the visibility was actually reduced. Therefore, we rearranged the data in a new *visibility* factor with three levels. The produced speed in the two conditions with a C_{RMS} of 0.86 was averaged and we labeled the new dataset as the *clear visibility* condition. The remaining data from the three levels of reduced contrast (0.47, 0.25 and 0.16) became the *gradually reduced visibility* condition and the *uniformly reduce visibility* condition for the gradient and uniform type of contrast reduction respectively. The results of this set of data are shown in figure 2.17.

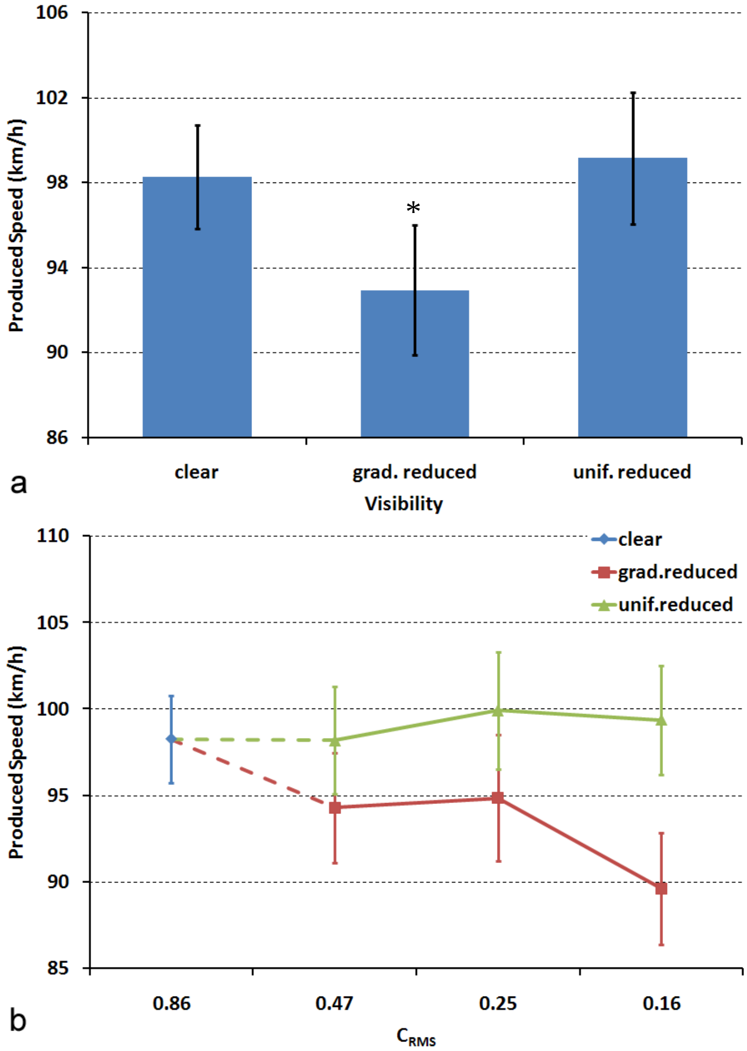

Figure 2.17: The produced speed in different visibility conditions. (a) The gradually reduced visibility condition causes the lowest produced speed, whereas the other two conditions do not differ significantly from each other. (b) None of the uniformly reduced visibility conditions differ significantly from the clear visibility condition or from each other. Dashed lines indicate the two original sets of data without distinction between clear and reduced visibility.

The visibility factor showed a significant main effect ($F(2,26) = 6.24$, $p < .05$). A post-hoc analysis revealed that only the produced speed under gradually reduced visibility condition was significantly lower compared to the clear condition. In the uniformly reduced visibility condition the produced speed was not affected when compared to the clear visibility condition (figure 2.17a). The interaction effect between type and amount of contrast reduction was not significant ($F(2,26) = 1.96$, $p = 0.16$) (figure 2.17b).

2.4.4. Conclusions

A general speed overproduction is consistent with our previous experiment (section 2.3) and also with other studies that have reported the same phenomenon as compensation for speed underestimation both in real and simulated driving conditions (Denton, 1980; Casey & Lund, 1987; Kemeny & Panerai, 2003).

We did not observe an increase of the produced speed in the uniformly reduced contrast conditions. This demonstrates that in a realistic driving simulation with wide field-of-view the driving speed is independent of a uniform reduction of the image contrast. Actually, the amount of contrast reduction used in our experiment is comparable to that of the original study by Snowden et al. (1998). Thus, we can exclude that the effect of speed overproduction was missing because of a weak contrast manipulation. It might be that the extent of the field-of-view and the richness of the environment, in terms of available motion cues, made the speed estimation process robust enough against the bias induced by the contrast reduction. In particular, the extent of the lateral field-of-view could have allowed the objects in the scene to stay visible for longer time. And this could have increased the reliability of the perceived speed.

We observed, in accordance with previous findings (Dyre, Schaudt, & Lew, 2005; Pretto & Chatziastros, 2006), that in the foggy scenario the participants produced a lower speed. This result supports once again the explanation stating that fog masks distal portions of the scene, leaving only the proximal parts with higher angular velocities visible. Furthermore, the trend of the produced speed provides additional support to this explanation. In fact, an increment of the fog density reduces the visible areas to the closer regions and we might then expect that the speed rate is increased accordingly. Moreover, the always visible road lines implemented in our behavioral experiment, together with the results on the perceptual level from the experiment 2 (section 2.2) allow us to rule out the possible influence of cognitive factors in the present results.

2.5. Further results and comparisons

It seems reasonable to assume that driving in reduced visibility conditions somehow impairs the driving performance. Therefore, in addition to the produced speed, we decided to measure the overall driving performance also in terms of trial duration, traveled distance and lateral shift within the lane. We recorded these set of data via the software interface during the three behavioral experiments presented so far (section 2.1, 2.3 and 2.4). These performance measures might be helpful in monitoring, understanding and interpreting the drivers' behavior. In particular, we believed that the time required and the distance traveled to accomplish the task, as well as the lateral deviation from the ideal centre of the lane, could be indicative of the difficulty of the task. For instance, we could expect an increase in the trial duration and the traveled distance as a consequence of a more demanding control of speed in foggy conditions. A sensible demand for the driver was indeed to reach and keep the target speed, and a reduced visibility of the landmarks in the environment might cause a loss of visual feedback for speed control. Moreover, the reduced visibility of approaching objects at the periphery of the visual field might lead the driver to shit laterally towards the central road markings in order to retrieve additional feedback on the current position. This lateral shift could be noticed and the driver would have to steer back towards the centre of the lane, increasing the instability (measured as standard deviation of the lateral position). Using the standard deviation of lateral position to measure a driver's ability to control the weaving of the car appears to be a very sensitive indicator of performance (Brookhuis, Volkerts, & O'Hanlon, 1990; Brookhuis, De Vries & De Waard, 1993; Lenne, Dietze, Rumbold, Redman & Triggs, 2003).

All data that have been merged for further analyses refer only to the target speed of 90 km/h and the fog density of 0.1, since these were the common conditions to all the experiments.

2.5.1. Produced speed

2.5.1.1. Results

The results obtained from the three behavioural experiments presented so far are shown in figure 2.18.

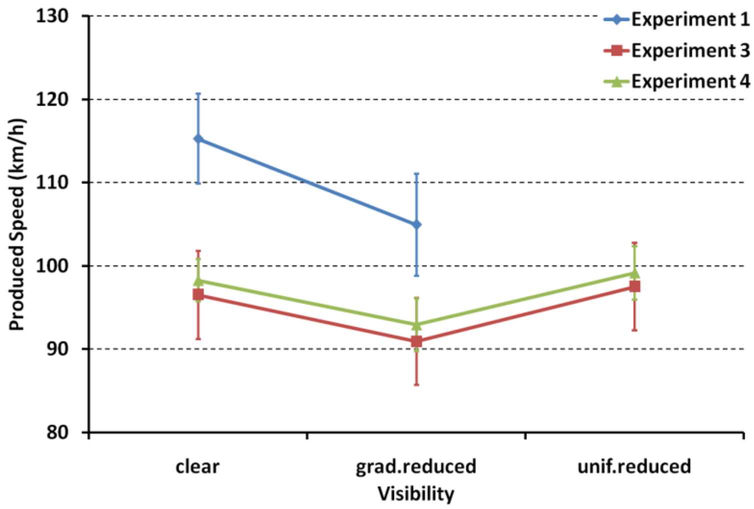

Figure 2.18: The produced speed in the three behavioural experiments, considered separately.

A comparison of the results indicates that the difference in the produced speed between the clear visibility condition and the condition with gradually reduced contrast looks very similar in all the experiments and tends to a reduction of speed. This reduction was significant in the three experiments and, additionally, in the experiments 3 and 4 there was no difference between the produced speed in clear and uniformly reduced visibility conditions. An ANOVA indicated that the average produced speed was significantly different between the experiments (F(2,35) = 3.47, p < .05). A post-hoc test (LSD) showed that in the first experiment the speed was significantly higher than in the other two experiments. In general, the shift could be explained as the impact of the different experimental setups. Narrowing the analysis to the common experimental conditions, we found no significant interaction between the results of the first experiment and the results of the other experiments. We could then merge the data that belong to the same experimental factors and plot the global results in a new graph (Figure 2.19). In fact, the absence of interaction effects means that the pattern of the response was the same in the three experiments.

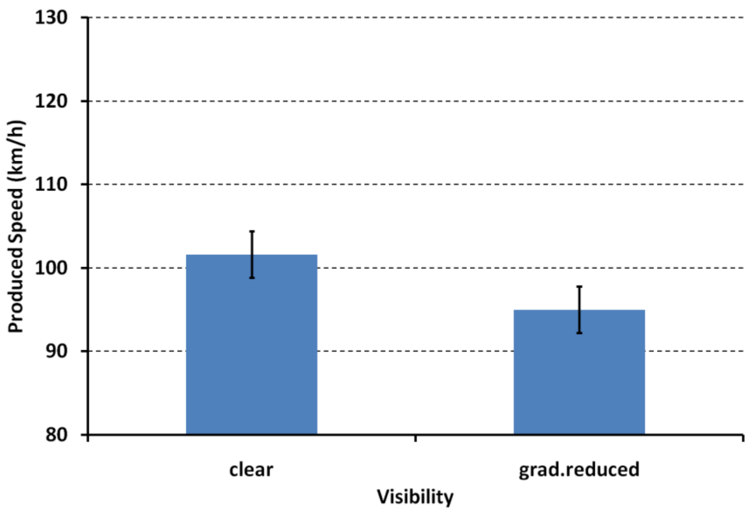

Figure 2.19: The produced speed in the three behavioural experiments, computed from data merged.

An ANOVA executed on the merged data showed a significant difference (F(1,35) = 30.85, p < .001) between the produced speed in the clear and gradually reduced contrast conditions.

2.5.1.2. Conclusions

The common trend of the produced speed found in all the experiments endorses the robustness of the findings that when driving in gradually reduced contrast the driving speed is decreased. This seems a result that holds through different manipulations like, as we did, the amount of contrast reduction, the extent of the field-of-view, the eye height, the training procedure and the driving setup. On the other hand, just these factors could be responsible for the difference in the absolute speed measured in the first experiment with respect to the other two experiments.

2.5.2. Trial duration

2.5.2.1. Results

As we already mentioned in the introduction to this section, the average trial duration can be considered as a measure of the difficulty of the task, depending on the experimental condition. In figure 2.20 we report the results of the three experiments.

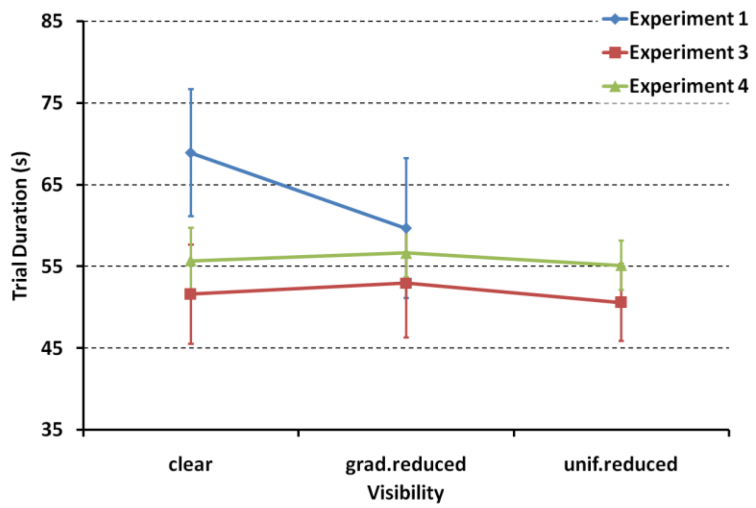

Figure 2.20: The trial duration in the three behavioural experiments, considered separately.

The three sets of data do not show significant differences, i.e. the average trial duration does not differ among the three experiments within a range from 52 to 64 seconds. In the first experiment only, the trial duration in clear and reduced visibility is significantly different ($t(8) = 2.72$, $p < .05$) and the latter condition results in shorter trials.

Because of the significant interaction effect between the experiment and the visibility conditions ($F(2,35) = 3.84$, $p < .05$), we could not assume a common pattern of response between the three experiments. Therefore we did not merge the data.

2.5.2.2. Conclusions

Surprisingly, in the first experiment the participants took less time to reach and stabilize the target speed when driving in foggy conditions than in clear visibility situations. This apparently counterintuitive result can be explained considering the *discomfort* of the participants during the most demanding foggy trials. In fact, because of the loss of visual information due to the effect of fog, participants might have preferred to accomplish the task more quickly than the usual time required in clear visibility conditions. We report here some facts that support this explanation.

The basic driving task required the execution of two concurrent sub-tasks: the lane keeping and the speed matching. The visual information indicating the path of the road, which is mainly in the central region of the drivers' visual field, was necessary for the accomplishment of both these tasks. In foggy conditions the distal information is the most affected by the contrast reduction. This leads to a loss of visibility in the region where the participants were prone to look at, i.e. straight ahead, centrally in their visual field. This situation is certainly a source of disease for the drivers. Moreover, the curved sectors of the path introduced even more demands in terms of driving control and made the predictability of the road path even more difficult. After a first straight piece of road, in fact, the path of the road started to bend quite frequently, and the basic driving activity might have turned into a more demanding task that the participants tried to shorten by reaching the target speed in advance.

Finally, the absence of any significant effect in the trial duration between the visibility conditions in the last two experiments could reflect the effectiveness of the white road-edge lines that we decided to keep unaffected by the contras reduction and fully visible at any distance. The similar duration of the trials could indicate that their difficulty was kept similar by this countermeasure, which allowed for a perfect predictability of the road path, as when driving in clear visibility conditions.

2.5.3. Traveled distance

2.5.3.1. Results

The average distance traveled in each trial is strictly connected to the trial duration and therefore we could expect a similar pattern in the results of the three experiments plotted in the graph below (figure 2.21).

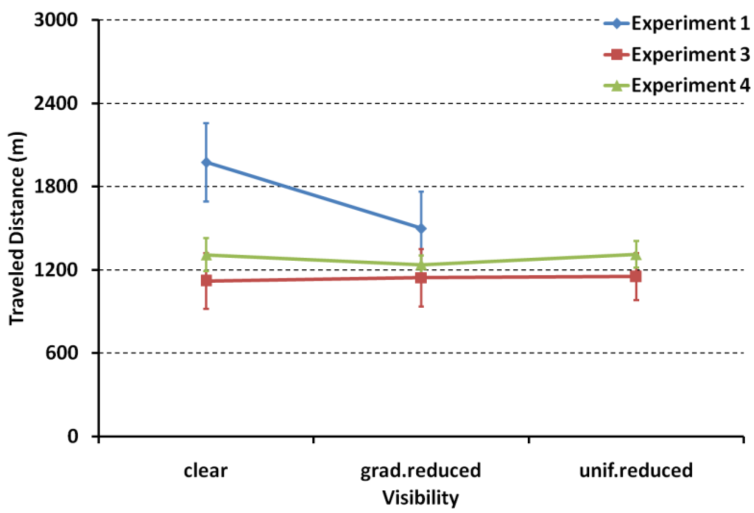

Figure 2.21: The trial duration in the three behavioural experiments, considered separately.

In the first experiment we found a significant difference of the traveled distance between the two visibility conditions ($t(8) = 3.34$, $p < .05$), whereas, in the other two experiments, the distance traveled was about 1200 meters, on average, independently of the experimental condition.

Because of the significant interaction effect between the experiment and the visibility conditions ($F(2,35) = 8.64$, $p < .005$), we could not assume a common pattern of response between the three experiments. Therefore we did not merge the data.

2.5.3.2. Conclusions

Here we can draw the same conclusions as in the previous paragraph 2.5.2.2, relatively to the trial duration. The flatted measurements of traveled distance in the last two experiments may prove the effectiveness of the perceptual cue that we have implemented to allow the predictability of the path even in foggy conditions. On the other side, the absence of these cues (the ever-visible white road-edge lines) might have been responsible of the greater difficulty of the foggy trials and could have induced the participants to terminate earlier.

2.5.4. Lateral shift

2.5.4.1. Results

In figure 2.22 we show the results of the visibility manipulations on the lateral shift, i.e. the displacement along the transverse axis of the road. We analyzed both the average lateral displacement of the virtual car from the ideal centre of the lane and the standard deviation of the displacement. The position relatively to the centre of the lane could be indicative of how much the contrast manipulations reduce the visibility of the peripheral landmarks, leading the drivers towards the still visible central line of the road (with two lanes). The standard deviation might be helpful to estimate the uncertainty of the drivers induced by the qualitatively different contrast manipulations implemented in our experiments.

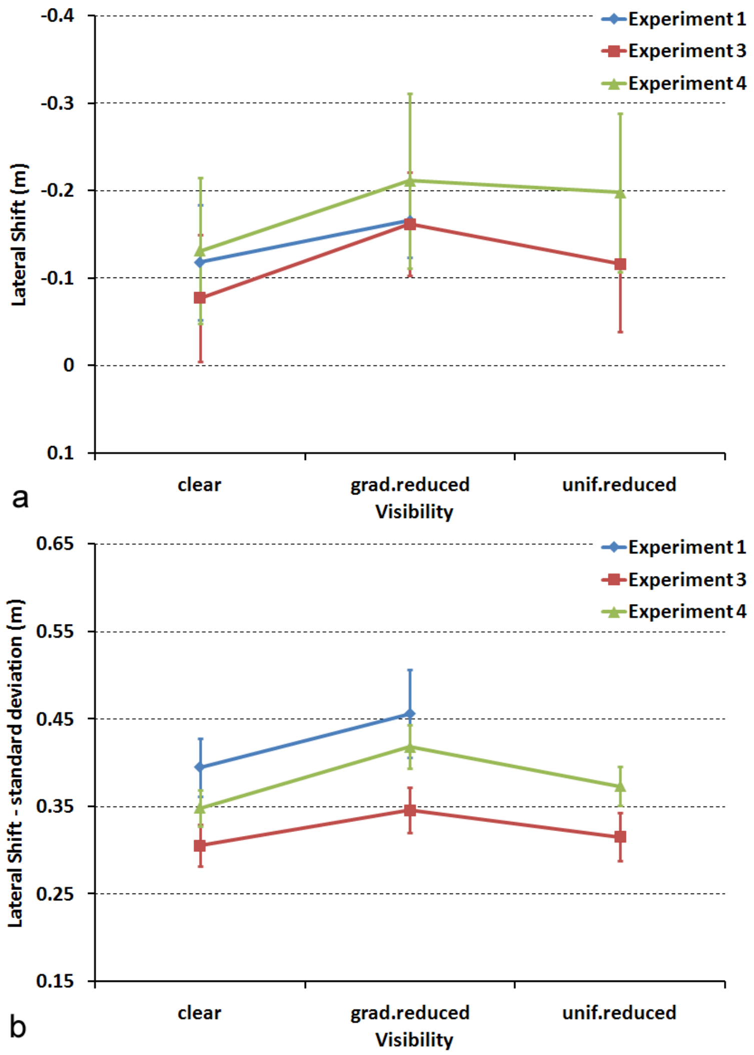

Figure 2.22: Lateral shift of the virtual car from the ideal centre of the lane. The average position, negative numbers indicate a shift to the left, positive to the right (a). The standard deviation of the lateral shift (b). The data of the three behavioural experiments are considered separately.

An ANOVA for repeated measures indicated that the lateral shift to the left of the ideal centre of the lane was never affected by the visibility manipulation, in any of the experiments (figure 2.22a). On average, the participants drove 15 cm to the left of the ideal position, i.e. closer to the central line of the road. The same statistical analysis executed on the merged data showed a significant effect of the gradually reduced contrast ($F(1,35) = 4.81$, $p < .05$) on the lateral position (figure 2.23a). On average, the drivers shifted their position 7 cm more to the left when driving in fog.

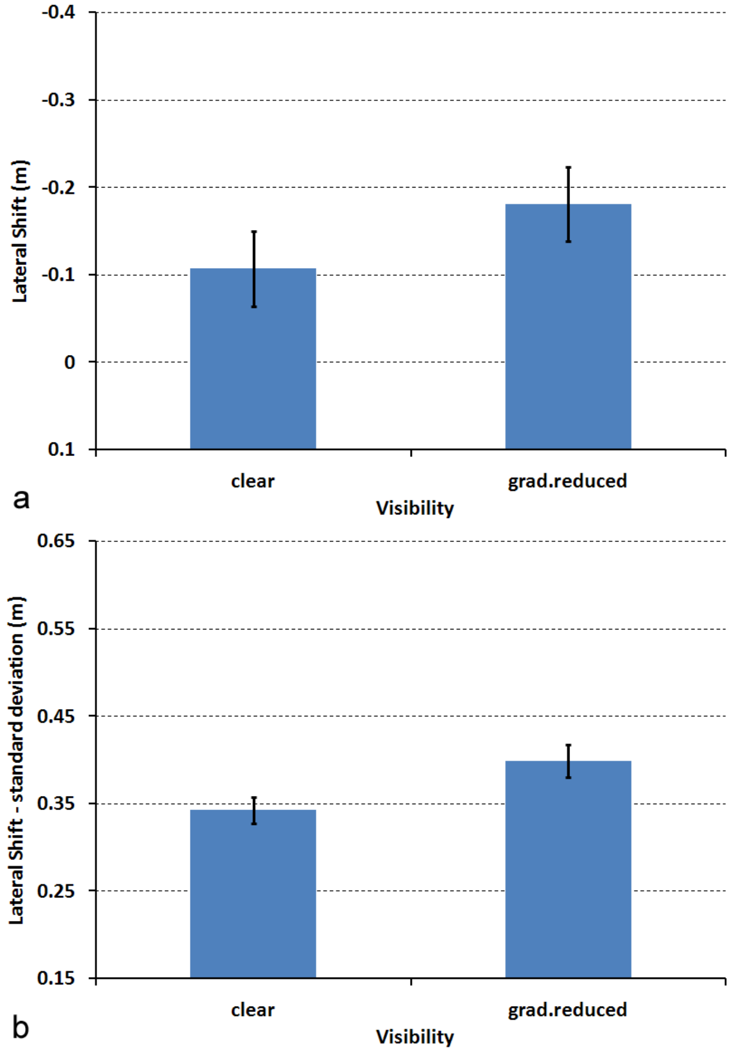

Figure 2.23: Lateral shift of the virtual car from the ideal centre of the lane. The average position, negative numbers indicate a shift to the left, positive to the right (a). The standard deviation of the lateral shift (b). The data of the three behavioural experiments are merged together.

The standard deviation of the lateral shift turned out to be significantly higher when driving in the gradually reduced contrast condition in each experiment ($F(1,8)$

= 6.34, $p < .05$; $F(2,28) = 4.38$, $p < .05$; $F(2,26) = 13.22$, $p < .001$ respectively, for the experiment 1, 3 and 4). A post-hoc test (Bonferroni) in the experiment 4 indicated also that the standard deviation was unaffected when driving in uniformly reduced contrast (figure 2.22b). Despite a significant difference between the values of the standard deviation in the three experiments ($F(2,35) = 3.57$, $p < .05$), there was no interaction effect between the experiments and the visibility conditions. We could thus merge the data and analyze the general effect independently of the differences in the experimental setups (figure 2.23b). As expected, we found that in the reduced visibility condition the standard deviation of the lateral position was higher ($F(1,35) = 29.85$, $p < .001$).

2.5.4.2. Conclusions

The lateral displacement of drivers on the lane has been previously investigated by other authors (Readinger, Chatziastros, Cunningham & Bülthoff, 2001; Horberry, Anderson & Regan, 2006). Here we found consistent results showing that there is a systematic bias to drive more to the left in comparison with the ideal centre of the lane. A reasonable explanation for this result would refer to the commonly experienced offset of the driver in normal cars. In fact, because of the symmetrical displacement of the seats in cars, while the cars are actually centered on the lane, the drivers are displaced to the left. Previous studies indicates that the amount of displacement is around 35 cm (Readinger *et al.*, 2001), which would roughly correspond to the driver's seat displacement with respect to the central axis of the car. In our study, likely because of the size of the vehicle mock-up and the central position of the driver's seat, the amount of displacement is reduced to 11 cm. We can assume that the bias induced by the driving experience is still present, just shrunk. It seems that driving in fog induces the drivers to steer towards the closest visible landmark, i.e. the line that separates the two lanes, as already mentioned in the previous paragraph. Unsurprisingly, decreased lateral control is linked to reduced visibility, as shown by the increased standard deviation on the lateral shift.

Therefore, the lower standard deviation found in the clear visibility conditions indicates that with visible road markings, drivers control the positioning of the vehicle on the road more accurately.

2.6. Uniform contrast reduction has no effect on the perceived speed, independently of the visual areas of stimulation

2.6.1. Introduction

In the previous experiment the uniform contrast reduction did not show any effect either on the perceived or on the produced speed. We hypothesized that the reason for this could be that the classical effect on perceived speed induced by uniform contrast reduction might be relevant only within the central area of the field-of-view, and that the additional information available from a large peripheral region might provide sufficient cues or sufficient time to allow for an accurate speed estimate. We tested this hypothesis in a psychophysical experiment where we manipulated in a within-subject design both the visible area of the field-of-view and the amount of uniform contrast reduction.

2.6.2. Method

2.6.2.1. Apparatus and stimuli

We run the experiment using the *Panolab,* as we did in the previous experiments (see par. 2.3.2.1).

In this study we were not interested in measuring the driving performance. Since the general mechanism of speed perception are supposed to work the same way both when dealing with high speeds domain, and when walking at relatively low speed, we implemented a simple virtual environment for simulating visual walking speeds. The participants were standing at 3.5 meters in front of the screen (Figure 2.24), at the eye height of 1.7 meters and the answer was provided by a two-buttons joystick that was held in the hand.

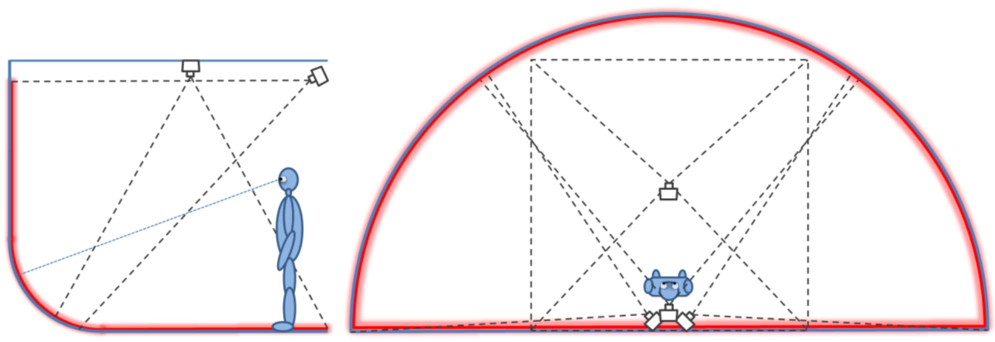

Figure 2.24: Lateral (a) and top (b) view of a schematic representation of the experimental setup. Dashed lines indicate the cones of projection of the four beamers. Glowing lines indicate the extent of the surface where the scene was projected.

The virtual environment consisted of a flat, grass-textured, ground surface extended to the horizon on a dark background (figure 2.25, top left picture). In order to manipulate the visible area of the scene we created three experimental conditions (full FOV, central area only, peripheral area only) in which a 40 degrees soft-edge disc-shaped transparent mask was implemented. In the *Full* FOV condition the environment was fully visible (figure 2.25, first row); in the *Central* area condition the mask occluded the peripheral portion of the scene and only the central 40 degrees were visible (figure 2.25, second row); and, finally, in the *Peripheral* area condition the center of the scene was occluded and only the outmost regions were visible (figure 2.25, third row). The contrast manipulation consisted of three conditions in which the image contrast (C_{RMS}) could be either unaltered (figure 2.25, first column), reduced to 50% (figure 2.25, second column) or, finally, reduced to 90% of the original image contrast (figure 2.25, third column). The contrast reduction was operated as described in section 2.3.2.1, and the compositing model was the same as described in the formula 2.4. In the present experiment the color of the transparent plane was set to black (RGB = [0,0,0]).

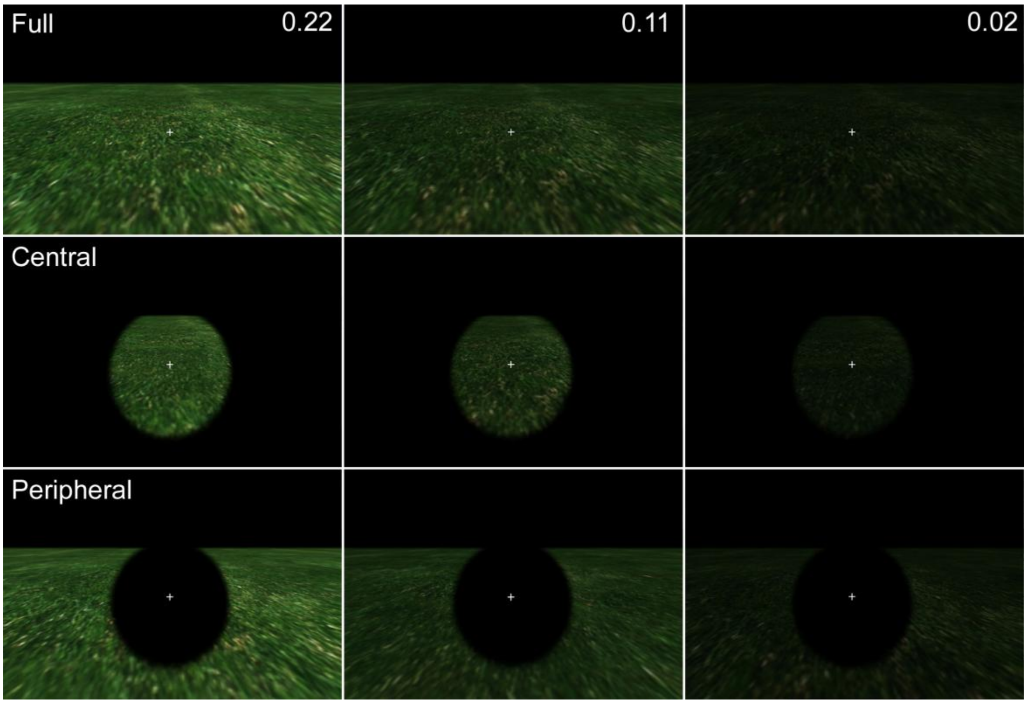

Figure 2.25: The experimental conditions. The three rows show, from top to bottom, the manipulation of the field-of-view (Full, Central or Peripheral) with, respectively, the full field visible, only the central area visible and only the peripheral area visible. The columns indicate, from left to right, the uniform contrast manipulation (C_{RMS} = 0.22, 0.11 and 0.2) with, respectively, the maximum contrast (100%), a reduction to 50% and a reduction to 90% of the original contrast.

2.6.2.2. Participants

Eight participants with normal or corrected-to-normal vision were recruited. They were paid and were naïve as to the purpose of the experiment. They were all experienced with psychophysical experiments.

2.6.2.3. Design and procedure

The experiment consisted of a two-interval forced-choice psychophysical task. The 6 experimental conditions tested were defined by the combination, in a within-subject design, of the two experimental factors described previously: the visible area of the FOV (Full, Central, Peripheral) and the uniformly reduced contrast of the image (C_{RMS} = .22, .11, .02). The reference scene was always displayed at the maximum contrast (C_{RMS} = .22) and could present one of the three visible areas indicated above (figure 2.25, first column). The test scene had the same visible area and could present one of the two levels of reduced contrast (C_{RMS} = .11, .02). For each trial, participants were asked to judge the speed of the two moving scenes displayed in one of the experimental conditions, and select which scene was perceived as moving faster. In figure 2.26 the typical time-course of a trial is described.

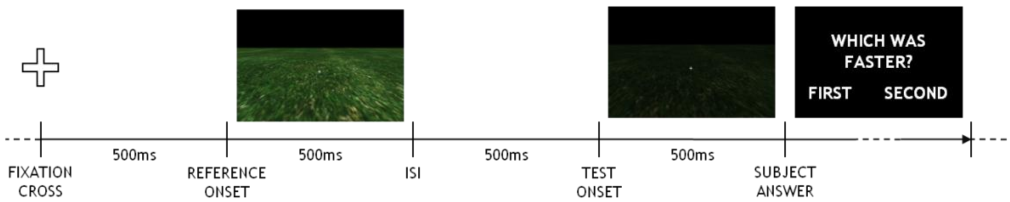

Figure 2.26: Trial example. A fixation cross appears at 20 degrees below the horizon, followed by the reference scene, which stays visible for 500 ms. An inter-stimulus-interval (ISI) of 500 ms separates the two scenes, with the test scene being displayed for another 500 ms. Then, the fixation cross disappears and a short sentence on the screen invites the participant to provide the answer by pressing one of two buttons. When a button is pressed, another trial starts.

The experimental conditions were randomly presented 80 times each for an overall number of 480 trials and an overall duration of about 1 hour per subject. The reference scene was moving always at the speed of 2 m/s, whereas the speed of the test scene varied from trial to trial according to an adaptive procedure. We used a procedure based on a Bayesian method (Kontsevich & Tyler, 1999) which defines the test speed of the following trial by optimizing the information that will be gained with the response, taking into account all the previous knowledge (e.g. tested values and subject answers). The optimization algorithm takes as initial parameters estimated ranges of the mean speed, the standard deviation, and the tested speeds, which were determined in a pilot experiment.

2.6.3. Results

We considered for statistical analysis the Point of Subjective Equality (PSE) [i.e. the speed at which the test scene was perceived to move as fast as the reference scene]. Results were pooled between all the participants and the PSE values for the experimental conditions can be seen in figure 2.27. The results did not show any significant bias in all the experimental conditions.

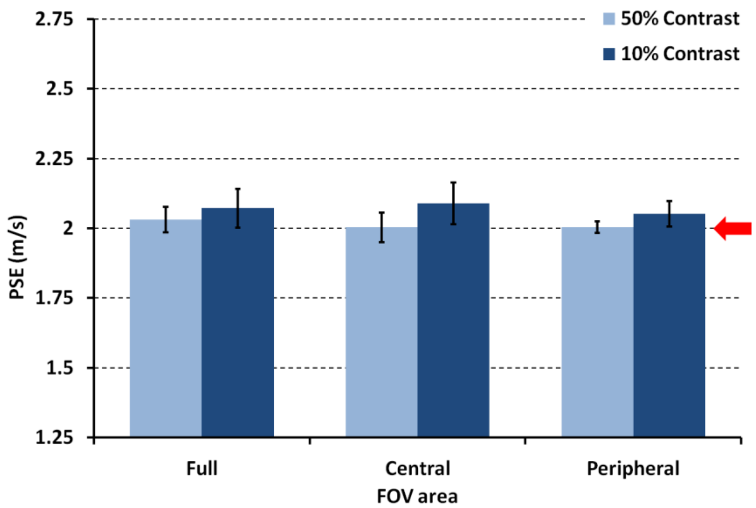

Figure 2.27: Results of the PSE. The arrow indicates the speed of the reference scene.

The One-Sample T-Test indicated that in none of the tested condition the perceived speed was significantly different from the reference speed. An analysis of variance for repeated measures (ANOVA) revealed not-significant effects for both the experimental factors.

2.6.4. Conclusions

These results undoubtedly indicate that in a realistic simulation the perception of the driving speed is independent of the amount of uniform contrast reduction and of the region within the field-of-view in which the reduction is applied (central or peripheral). Similar results of a substantial insensitivity to contrast degradation were found by de Grind, Koenderink and van Doorn (1987) in a study on the foveal and peripheral detection of coherent motion in moving random-dot patterns. The reason why we could not find any effect of the uniform contrast reduction might find an explanation considering that the luminance range of our stimuli was nearly within the range of the mesopic vision, where the vision partially mediated by rods seems less sensitive to contrast variations (Gegenfurtner *et al.*, 1999). An alternative explanation rests on the assumption that the visual system can effectively adapt to different contrast, similar to the process of luminance adaptation. These points will be discussed further in the Chapter 4.

Chapter 3

Effects of field-of-view and gaze direction on the perceived speed

The retinal projection of linear self-motion is described by an expanding optic flow, which is composed of different angular velocities depending on direction and distance to the observer (Gibson, 1950). For instance, during forward motion, the very close region in the environment results in higher angular velocities. While driving, the lower angular velocities coming from the distant region are usually in the centre of the driver's visual field. We assume that when the central region is occluded, like in a foggy scenario, the only available information comes from the periphery, which leads to higher perceived speeds. In the same way, when the peripheral region is missing, lower angular velocities from the central region lead to lower perceived speeds. We believe that in the speed estimation process during forward self-motion, the velocity signals coming from the different regions of the visual field have to be integrated into a single estimate of the own speed. In this chapter we report some experiments that we developed in order to investigate how retinal angular velocities are taken into account to estimate the linear self-speed.

3.1. Central and peripheral regions affect differently the perceived driving speed

3.1.1. Introduction

In the previous experiments we have shown that the behavior of participants changes when driving in fog. From this result we could infer that the speed was perceived differently according to the different visibility conditions. In the psychophysical experiment described in section 2.2 we have already proven that simulated fog increases the driver's perceived speed. We found that in order to perceive the driving speed as fast as the driving speed in clear visibility conditions the actual speed had to be lowered by as much as 13% at 90 km/h. In the present experiment we intend to prove that the measured behavioral effect is caused by a change in the visible area of the field-of-view. Therefore we use a psychophysical methodology, which does not include a speed production task but rather introduces two-dimensional manipulations of the field-of-view, in order to examine directly how the speed is perceived (Brandt, Dichgans, & Koenig, 1973). The explanation provided so far for the behavioral results assumes that the compensation for the different angular velocities coming from either the periphery (high angular velocities) or the center (low angular velocities) of the field of view is not perfect. In particular we assume that the availability of high angular velocities from near regions directly increases the estimated speed. On this basis we formulated two hypotheses: when the visibility of the central region of the field of view is precluded we expect a higher perceived speed, and, on the other hand, when the peripheral region of the FOV is not visible, we expect a lower perceived speed. In this experiment we examined whether speeds of forward translations can be accurately perceived when only limited regions of the FOV are visible.

3.1.2. *Method*

3.1.2.1. *Apparatus and stimuli*

The same experimental setup as the previous experiments was used. Two buttons on the steering wheel of the driving mock-up where used in the experiment.

Because of the perceptual task of this study, we did not measure driving performance, and thus we modeled a straight road section instead of the previous complex road path. We kept all the other visual features described in the previous experiment: traffic divider, road poles and markings. We created three different scenarios (*fully visible*, *centre visible*, *periphery visible*) in which a 40 degrees soft-edge disc-shaped transparent mask was implemented. In the scenario with full field-of-view (Full) the environment was fully visible (figure 3.1a); in the central area scenario (CV) the mask occluded the peripheral portion of the scene and only the central 40 degrees were visible (figure 3.1b); and, finally, in the peripheral area scenario (PV) only the outer regions were visible (figure 3.1c).

Figure 3.1: The virtual environment with three different transparent masks: the scene entirely visible (a), the central region visible (b), and the peripheral region visible (c).

3.1.2.2. *Participants*

Eight participants with normal or corrected-to-normal vision were recruited. They were paid and were naïve as to the purpose of the experiment.

3.1.2.3. Design and procedure

The experiment consisted of a two-interval forced-choice psychophysical task. The experimental conditions were defined by a pair of visibility masks that were applied to the first and the second moving scene presented. The four conditions tested were: Full-PV; Full-CV; PV-CV and CV-PV. For each trial, participants were asked to judge the speed of the two moving scenes displayed in one of the experimental conditions, and select which scene was perceived as moving faster. In figure 3.2 the typical time-course of a trial is described.

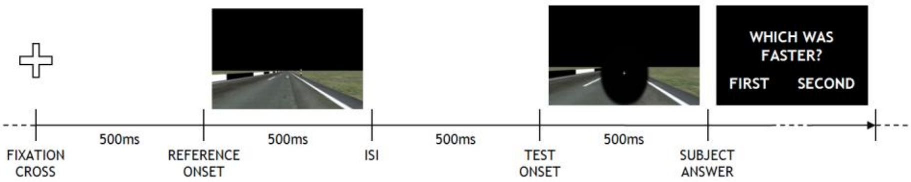

Figure 3.2: Trial example. A fixation cross appears at 4 degrees below the horizon, followed by the reference scene, which stays visible for 500 ms. An inter-stimulus-interval (ISI) of 500 ms separates the two scenes, with the test scene being displayed for another 500 ms. Then, the fixation cross disappears and a short sentence on the screen invites the participant to provide the answer by pressing one of two buttons. When a button is pressed, another trial starts.

The four experimental conditions were randomly presented 80 times each for an overall number of 320 trials and an overall duration of 40 minutes per subject. The reference scene was moving always at the speed of 90 km/h, whereas the speed of the test scene varied from trial to trial according to the adaptive procedure described in section 2.6.2.3.

3.1.3. Results

We considered for statistical analysis the Point of Subjective Equality (PSE). Results were pooled between all the participants and the PSE values for the experimental conditions are shown in figure 3.3. Despite small individual differences in the various conditions, the same general pattern was evidenced in all participants.

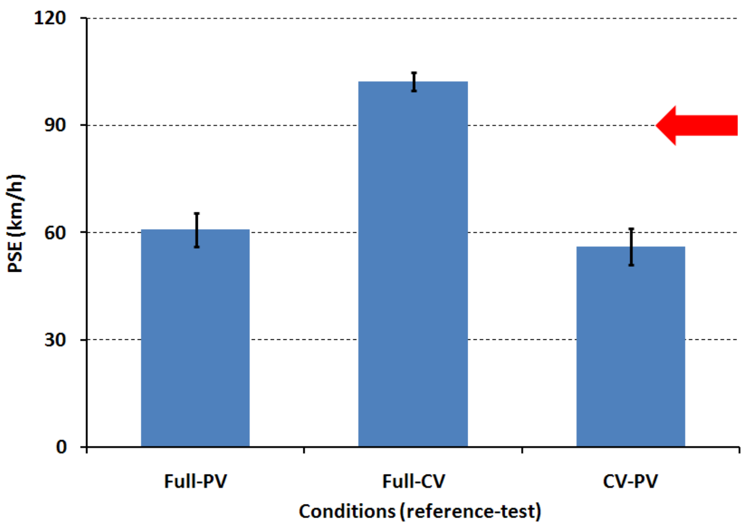

Figure 3.3: PSE of the perceived speed. The conditions PV-CV and CV-PV have been merged. The arrow indicates the reference speed.

In figure 3.3 the data are plotted to show the estimated PSE. The results of the PV-CV and CV-PV conditions were merged, since both conditions differed only in the order of presentation. This arrangement allows us to visualize the bias induced by the angular velocities from the different regions of the field-of-view. For instance, in the Full-PV condition, the speed of the test scene with only the peripheral region visible had to be lowered to 60 km/h in order to be perceived as moving as fast as the 90 km/h reference speed. This means that the perceived speed at the periphery was much higher than that of the entire scene visible. An ANOVA for repeated measures indicated that the PSEs differed significantly ($F(2,14) = 58.03$, $p < .001$) and a corrected post-hoc test (Bonferroni) revealed that all the three conditions were significantly different one another.

At the one-sample t-test analysis we found that the speed in the periphery had to be significantly lowered to be perceived as moving equally fast as the speed of any of the other reference conditions, either full FOV or central vision. Conversely, the speed in the center had to be considerably increased when compared to the speed of the peripheral vision condition (Table 3.1: PV-CV), but only slightly (and still significantly) increased when the reference scene was fully visible (Table 3.1: Full-CV).

One-Sample T-Test (test value = 90 km/h)

Condition	PSE (m/s)	St.Err. PSE	$t(6)$	Sig. (p)
Full-PV	60.85	4.402	-6.624	.000
Full-CV	102.26	2.398	5.113	.001
PV-CV	163.84	14.366	5.140	.001
CV-PV	59.69	4.735	-6.403	.000

Table 3.1: The table presents the estimated PSE, the standard errors, the computed value of the one-sample t-test and the associated significance probability for all the four original conditions.

3.1.4. Conclusions

These results clearly show that the perceived speed during forward motion is strongly affected by the available velocity signals from the scene. According to our predictions, people cannot accurately compensate for the different velocity signals available when only limited regions of the FOV are visible. When the central region of the field-of-view is occluded the speed at the periphery is perceived as being higher, and conversely, when the information from the peripheral region is missing the speed at the center is perceived as being lower. The speed underproduction effect measured in the foggy scenario of the previous experiments seems therefore to derive from a speed overestimation effect, which is already present at the perceptual level, and caused by the “mask” effect of fog on the central region of the visual field.

In the condition where the visual information from the central region is always present, the measured PSE indicates that the speed is nearly correctly estimated, although the missing peripheral region could in principle bias the result. However, the effect on the perceived speed is significantly lower when compared to the effect elicited when only the peripheral region is visible. Therefore, from the comparison between these two conditions, we are allowed to conclude that the central vision is certainly necessary and seems to be almost sufficient to correctly estimate the constant speed of forward self-motion. Conversely, the influence of the peripheral region on the perceived speed seems to be less relevant, although the largest bias was obtained comparing the central and peripheral regions directly.

Finally, our results indicate that despite a conceivable effect of the periphery, a central field of view of 40 degrees is already sufficient to provide a nearly correct estimate of the traveling speed.

3.2. Central and peripheral regions affect differently the perceived walking speed

3.2.1. Introduction

This experiment was intended to provide external validity to the previous experiment by extending the manipulation of the areas of the field of view to the domain of the walking speed. Other minor changes were implemented, like a simplified, but still ecological, virtual environment, which provided less motion cues than the driving scenario; and a different eye height, due to the standing position of the participants. Furthermore, this experiment served as control to the findings of the experiment described in 2.6, where the non-significant results could derive from the fact that the perceived speed is independent of the visual area of stimulation when dealing with relative low speeds. For these two purposes we kept the same experimental settings and virtual environment as reported in section 2.6, and tested the effect on perceived speed of different visual areas of stimulation using the methodology described in section 3.1.

3.2.2. Method

3.2.2.1. Apparatus and stimuli

The same experimental setup as described in the paragraph 2.6.2.1 was used. The virtual environment was similar to the one used in the experiment described in section 2.6 and consisted of a grass textured ground plane extended to the horizon on a dark background (Figure 3.4). A 40 degrees soft-edge disc-shaped transparent mask was implemented in order to select three visible areas of the scene: full image visible (Figure 3.4a), central area visible (figure 3.4b) and peripheral area visible (Figure 3.4c).

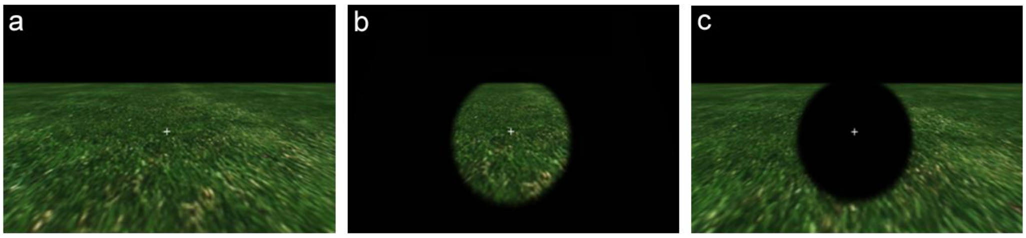

Figure 3.4: The virtual environment with three different transparent masks: the scene entirely visible (a), the central region visible (b), and the peripheral region visible (c).

3.2.2.2. Participants

Seven participants with normal or corrected-to-normal vision were recruited. They were paid and were naïve as to the purpose of the experiment.

3.2.2.3. Design and procedure

We used the same procedure of the previous experiment, i.e. a two-interval forced-choice psychophysical task. We tested a combination of four conditions as we did in the previous experiment (see paragraph 3.1.2.3): Full-PV; Full-CV; PV-CV and CV-PV. For each trial, participants were asked to judge the speed of the two moving scenes displayed in one of the experimental conditions, and select which scene was perceived as moving faster. The typical time-course of a trial was the same as presented in figure 3.2. The four experimental conditions were randomly presented 80 times each for an overall number of 320 trials and an overall duration of 40 minutes per subject. The reference scene was moving always at the speed of 2 m/s, whereas the speed of the test scene varied from trial to trial according to an adaptive procedure, as described in 2.6.2.3.

3.2.3. Results

We considered for statistical analysis the Point of Subjective Equality (PSE). Results were pooled between all the participants and the PSE values for the experimental conditions are presented in Table 3.2.

One-Sample T-Test (test value = 2 m/s)

Condition	PSE (m/s)	St.Err. PSE	$t(6)$	Sig. (p)
Full-PV	1.79	.071	-2.97	.025
Full-CV	2.14	.081	1.69	.143
PV-CV	2.35	.136	2.57	.042
CV-PV	1.77	.073	-3.22	.018

Table 3.2: Results. The estimated PSE, the standard errors, the computed value of the one-sample t-test and the associated significance probability for all the conditions.

At the one-sample t-test analysis we found that the speed in the peripheral area of the scene had to be significantly lowered to be perceived as moving equally fast as the speed of any of the other reference conditions, either with the full scene (Table 3.2, Full-PV) or only the central area visible (Table 3.2, CV-PV). Conversely, the speed in the central area of the scene had to be increased when compared to the speed in the periphery (Table 3.2, PV-CV). Finally, when the reference scene was fully visible, the speed of the central area was perceived as correct (Table 3.2, Full-CV).

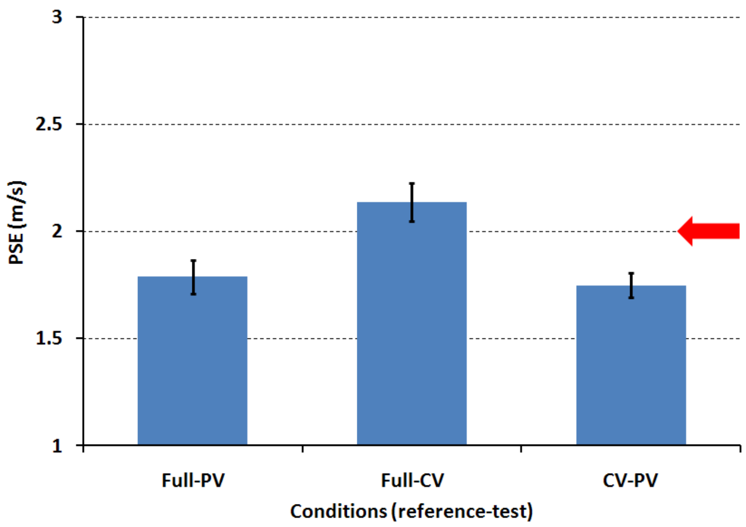

Figure 3.5: PSE of the perceived speed. The conditions PV-CV and CV-PV have been merged. The arrow indicates the reference speed.

In figure 3.5 the data are plotted to show the estimated PSE. The results of the PV-CV and CV-PV conditions were merged, since both conditions differed only in the order of presentation. As a result, the speed of the test scene with only the peripheral region visible had to be lowered to 1.75 m/s in order to be perceived as moving as fast as the 2 m/s reference speed from the central region. A repeated-measures ANOVA indicated that the PSEs differed significantly among the three conditions ($F(2,12) = 7.13$, $p < .05$).

3.2.4. *Conclusions*

Here we can draw the same conclusions as for the previous experiment, relatively to the influence of the available velocity signals from the scene on the perceived speed during forward motion. When the central region of the visual field is occluded the speed at the periphery is perceived as being higher, and conversely, when the information from the peripheral region is missing the speed at the center is perceived as being lower.

In the condition where the visual information from the central region is always present, both in the reference and in the test scene, the measured PSE indicates that the speed is correctly estimated. Therefore, we are allowed to conclude that the visibility of the central region is necessary and totally sufficient to correctly estimate the speed of self-motion in forward translation. Furthermore, when the central area is visible, the additional information from the peripheral region seems to be irrelevant.

Finally, as in the previous experiment, these results indicate even more clearly that a central field of view of 40 degrees is already sufficient to provide a correct estimate of the self speed.

3.3. *Effects of gaze direction and restricted field-of-view on the perceived walking speed*

3.3.1. *Introduction*

During linear self-motion at constant speed, the retinal speeds of stationary objects vary as a function of their declination angle, i.e. the vertical angle between the gaze direction and the horizontal plane (Figure 3.6). Nevertheless, when we move in our environment, we do not feel that different places move at different speeds. A compensation mechanism is thought to mediate between retinal angular velocities and perceived linear speed [i.e. speed computed on a linear distance] so that velocity constancy is achieved.

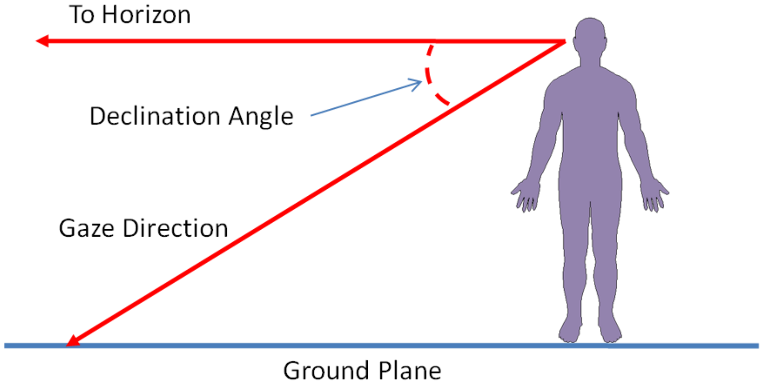

Figure 3.6: Angle of declination.

In a recent study (Pretto and Chatziastros, 2006) it has been shown that the perceived speed is altered when driving with a reduced field-of-view. The explanation proposed in that study leads us to the hypothesis that, when moving at constant speed, humans might not be able to compensate for the different velocity signals coming from various declination angles when only a limited portion of the visual field is visible. In the previous experiment we have already shown that the available velocity signals from either the centre or the periphery of the scene influences the speed estimate of linear self-motion. Here we address more specifically the question whether gazing at different angles, either with the full field available or with a restricted view of the central area, might induce a bias in the perceived walking speed.

3.3.2. Method

3.3.2.1. Apparatus and stimuli

The experimental setup, as well as the virtual environment, was the same as in the previous experiment (see 2.6.2.1). We manipulated the extent of the field of view to compare the speed perceived from a fully visible scene (*Full* condition) and the speed perceived from a scene that is visible only through an aperture of 40°(H) × 6° (V) in the central region (*Limited* condition), as shown in figure 3.7.

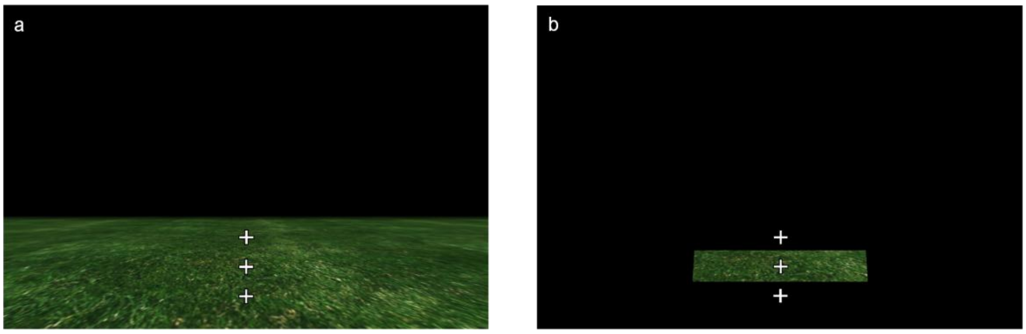

Figure 3.7: (a) the full FOV condition as it appeared to participants; (b) the limited FOV condition, with an aperture of 40º×6º. Crosses indicate the fixation points at the three declination angles.

We manipulated also the gaze declination angle (12°, 20° and 28°), which corresponded to positions on the plane located at a distance of 8, 4.7, and 3.2 m, respectively (Figure 3.8).

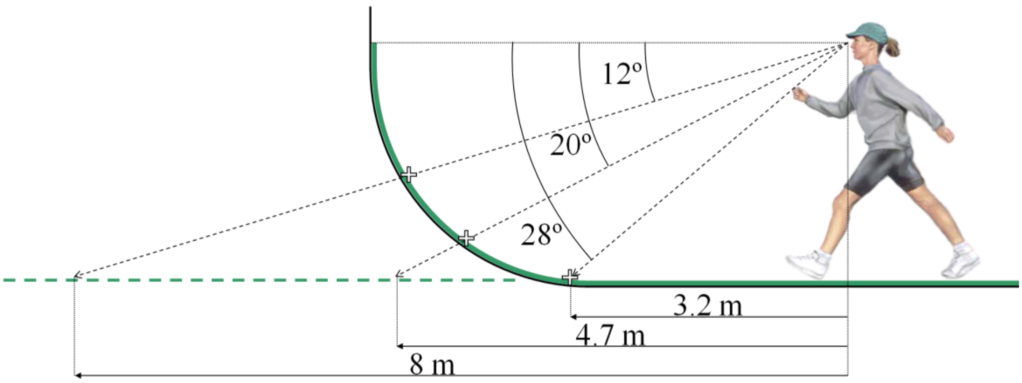

Figure 3.8: Experimental factors. The open field is projected on the curved screen (green line) but it appears as being a flat plane that extends to the horizon. The declination angles correspond to positions on the plane located at a distance of 8 m, 4.7 m, and 3.2 m.

3.3.2.2. Participants

The participants (6 males and 6 females) had normal or corrected-to-normal vision. They were paid and were naïve as to the purpose of the experiment.

3.3.2.3. Procedure

We measured the visual perceived speed at eye-height (1.7m) while simulating fast walking speeds on a virtual open field. We used a two-interval forced-choice procedure (2IFC) with constant stimuli method in a 2 (field of view) × 3 (declination angles) within-subjects design. We tested eight different speeds ranging from 0.67 to 6 m/s. The reference stimulus appeared always in the intermediate declination angle at the speed of 2 m/s. A fixation cross appeared at the desired declination angle 500 ms before each stimulus. At every trial, subjects had to select which of the two presented stimuli indicated a faster forward speed of translation.

3.3.3. Results

At the repeated-measures ANOVA we obtained a significant effect of the declination angle ($F(2,22) = 14.16$, $p < .005$). A post-hoc test (LSD) indicated that in both full FOV and limited FOV condition the PSEs of the three declination angles differed significantly. This result shows that when gazing more centrally the perceived speed is lower (higher PSE) than the speed perceived at the reference angle. On the other hand, when gazing more peripherally the speed is perceived higher (lower PSE) than the speed at the reference angle (Figure 3.9).

In general, the sensitivity of the participants for speed discrimination was fairly high and did not show any trend or noticeable change between conditions.

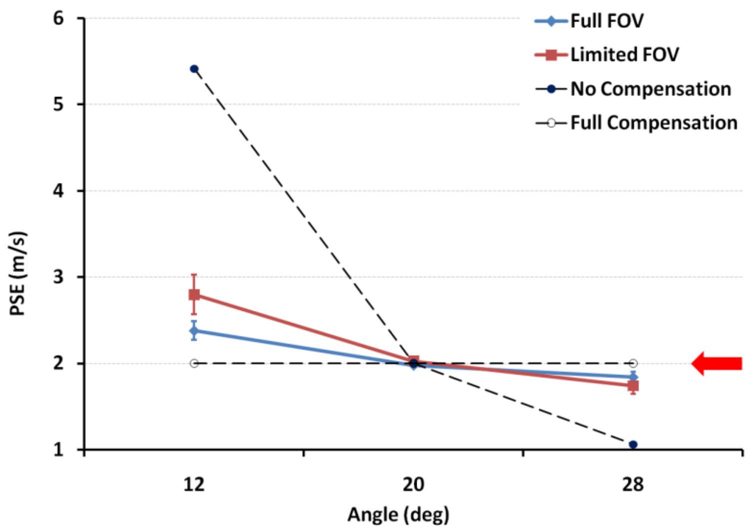

Figure 3.9: PSEs. Dashed lines indicate the expected results in case of full compensation (empty circles) and no compensation (full circles) for the angular velocities at the corresponding angles. The arrow indicates the reference speed (2 m/s).

We obtained also a significant interaction between the extent of the field of view and the declination angle ($F(2,22) = 6.07$, $p < .01$), with an accentuated effect in the limited FOV condition.

3.3.4. Conclusions

The results indicate that walking speed can be accurately discriminated in virtual environments when gazing at the same fixation point. In fact, in the control condition with both the reference and the test scene at an identical declination angle of 20 degrees the perceived speeds are the equivalent.

The graph in Figure 3.9 shows which PSEs we would have expected to be measured in case of full compensation and absence of compensation. The computed compensation score for the angular speeds was actually in the range between 75% (28°, Limited FOV) and 89% (12°, Full FOV), with an average value of 80%. This means that the retinal angular velocities deriving from the optic-flow patterns affect the estimate of the linear self-speed during forward translation, and consequently induce a bias. Furthermore, the present results suggest that limiting the FOV impairs the compensation mechanism even more.

3.4. Effects of incongruent velocities between central and peripheral regions on driving speed.

3.4.1. Introduction

In driving simulations, the perception of the speed of self-motion relies mostly on visual information (Bartmann, Spijkers and Hess, 1991): even with motion cueing, vestibular and proprioceptive feedback can be either limited due to technological constraints (limited range of physical motion) or not informative (straight drive at constant speed). An important source of information for speed perception is the optic flow in the virtual driving environment. The optic flow (Gibson, 1950) is defined as the perceived visual motion of objects as the observer moves relative to them, and its role has been demonstrated for the perception and control of speed during walking (Baumberger *et al.*, 2000) and flying (Larish and Flach, 1990). During walking, changes in the velocity of the visual ground, thus altering the optic flow, lead to unintentional modulation of walking speed (Prokop *et al.*, 1997): a backward flow leads to a decrease in walking speed, whereas a forward flow leads to an increase in walking speed. The main question of the present study was whether altered optic flow in a driving situation affects speed choice in a manner similar to the walking situation. To answer this question we manipulated the relative motion of the road surface along the driving direction.

3.4.2. Method

3.4.2.1. Apparatus and stimuli

Since the manipulations presented here were run as part of the within-subject design of the first experiment described in the previous chapter (section 2.1) we shared the same facilities, the driving interface (paragraph 2.1.2.1) and the procedure (paragraph 2.1.2.3).

We manipulated the motion of the road surface along the driving direction. The experimental manipulations included 3 target speeds (40, 60, and 90 km/h) and 3 relative road speeds (*faster*, *same* and *slower*). The relative road speed factor was implemented by scrolling the road's texture relative to the current driving speed (Figure 3.10).

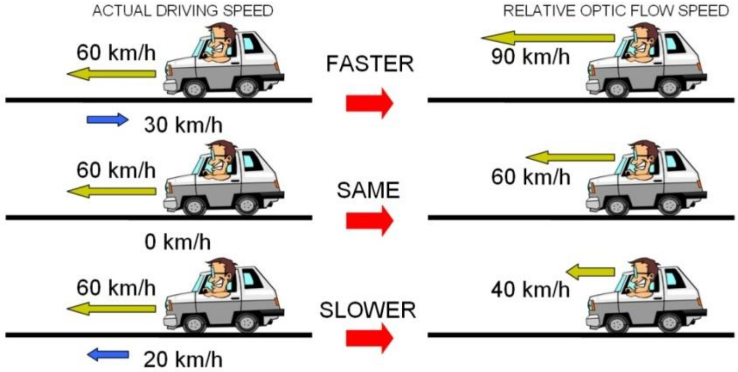

Figure 3.10: The "relative road speed" factor. Left: the arrows in front of the car indicate the actual driving speed, while the arrows beneath the road (black horizontal line) indicate the speed and the direction of the road texture scrolling. Right: the arrows indicate the expected perceived speed, if the speed judgments rely only on the optic flow of the road's surface.

In the *faster* condition, the optic flow from the road surface appeared faster compared to the actual driving speed, since the texture of the surface was moved opposite to the driving direction (Figure 3.10, top). The speed of texture motion was always equal to 50% of the current driving speed. Similarly, in the *slower* condition, the texture was moved in the direction of driving (33% of the current driving speed) and the resulting optic flow from the road surface indicated a slower driving speed (Figure 3.10, bottom). The apparent speed in these two conditions amounted to 150% or 67% of the actual driving speed with regard to the motion of the rest of the environment. In the control condition *same*, the optic flow corresponded to the actual driving speed (Figure 3.10, center). The manipulation factor was set to 1.5 after a pilot experiment had shown that no observer noticed a visual conflict with this amount of road texture scrolling.

3.4.2.2. Participants

The participants were the same as in the experiment 1 (see 2.1.2.2). Nine subjects (4 females and 5 males) with normal or corrected-to-normal vision participated in the study. All participants had a valid driving license for at least five years and were considered as experienced drivers since they declared an everyday car usage. They were paid and were naïve as to the purpose of the experiment.

3.4.2.3. Design and procedure

The three experimental conditions of the “relative road speed” factor were randomly interleaved within the same experimental design of the first experiment, for an overall number of 18 conditions (3 target speeds × 2 visibility conditions × 3 relative road speeds).

The training phase has already been described in the Section 2.1.2.3.

The average speed produced during the last five seconds of each trial was considered as the produced speed for the statistical analysis.

3.4.3. *Results*

We found a significant main effect of the relative road speed factor ($F_{(2,16)}$=80.11, p<.001). Participants increased the driving speed on average by 25 km/h (35%) when the texture motion indicated a slower speed and decreased by 7 km/h (-10%) when the driving speed appeared faster (figure 3.11). Interestingly, the amount of speed compensation appeared to be constant over the tested target speeds and not proportional to the driving speed.

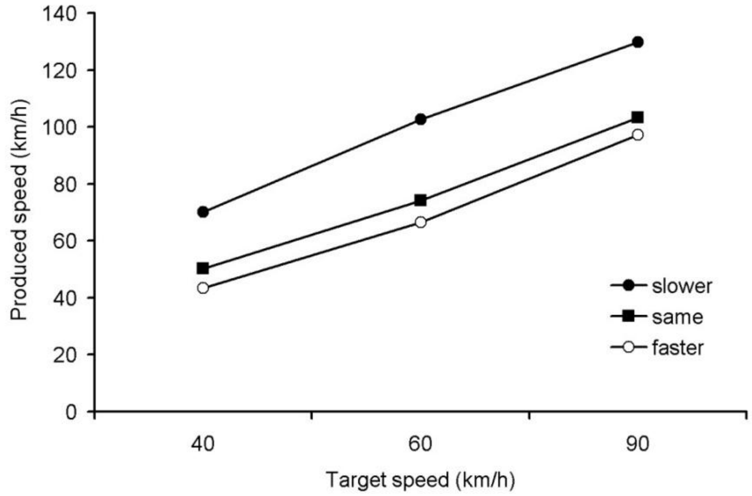

Figure 3.11: Effects of the "relative road speed" factor. With a road surface moving slower than the rest of the environment, drivers increased their driving speed, and vice versa.

3.4.4. *Conclusions*

In this study we have shown that the optic flow coming from the road ahead strongly affects the produced speed, despite the presence of other motion cues in the periphery of the environment that provide a consistent information about the actual driving speed. This demonstrates the importance of the central portion of the scene and its dominant role for the estimation of the actual driving speed. Further discussion will be presented in the next chapter.

Our results go in the same directions as previous findings during walking: with an increased optic flow rate we slow down, with slower optic flow we speed up. The present effects are even more pronounced compared to the effects during walking. The interpretation of this might be that during walking a direct matching between physical effort and speed exist, but no equivalent source of information during driving. This emphasizes once more the role of visual motion and optic flow for speed estimation in driving simulations.

A psychophysical study that directly compared thresholds for radially expanding and contracting optic-flow stimuli found greater sensitivity to contracting patterns (Edwards & Badcock 1993). Similarly, thresholds for the detection of linear vection, measured in terms of minimum image speed required to induce a sense of self-vection, are lower for backward motion than for forward (Berthoz, Pavard & Young, 1975). A recent study (Edwards & Ibbotson, 2007) has shown that the visual system is more sensitive to large-field radially contracting stimuli than to expanding ones and that there are no consistent differences between the sensitivities to large-field radial stimuli that contain positive, negative, or random speed gradients. Given that full-field stimuli (diameter of 82 deg) were used in the experiments, the authors assume that the results reflect the relative sensitivities of the optic-flow system.

Moreover, the present findings suggest that higher speed estimations will be obtained by scrolling the texture of the ground opposite to the driving direction, without any change in the geometry or the contrast of the scene. This effect could be exploited in driving simulators in which a general speed underestimation is reported.

Chapter 4

General discussion and conclusions

4.1. Summary of results

In the course of the presented work we have collected several results. Here we provide a summary of the main results that we are going to comment in more details in the following sections.

A realistic implementation of contrast reduction in a driving simulation leads to a lower produced speed of self-motion (section 2.1). This behavioral effect has a perceptual origin, given that in the same virtual environment with realistic fog conditions the perceived speed is increased (section 2.2). The perceived and produced driving speeds are consistently altered only at the higher tested speeds, namely 60 and 90 km/h. Conversely, at the lower target speed (40 km/h) an exponential reduction of the image contrast as a function of distance shows no effect. When the image contrast is uniformly decreased all over the visual scene the perceived speed is reduced, accordingly to the results from previous studies (Distler & Bülthoff, 1996; Snowden, Stimpson & Ruddle, 1998). This result has been found only once in the first of two driving simulation setups that we used in the experiments (see section 2.1.2.1 for a description).

In the third experiment (section 2.3) we replicated the findings of our first study. The produced speed under foggy conditions (gradually reduced contrast) is significantly lower in comparison with the produced speed of clear visibility conditions. This result evidently indicates that the perceived speed is increased when driving in fog. The *Panolab* setup provides more ecological validity to this result, given that the field-of-view of the driver is stimulated also in the peripheral region. In the same setup we found that a spatially uniform reduction of the image contrast, as operated by Snowden, Stimpson and Ruddle (1998) does not alter the driving speed. We discuss possible explanation for this result in the next section.

The results of experiment 4 (section 2.4) demonstrate that the driving speed is unaffected by any change in the amount of uniform contrast reduction. On the other side they reveal that drivers react to increasing fog density by reducing the driving speed. A reduction of 80% in the image contrast (increase of fog density) causes a decrease of 9% in the driving speed, while a reduction of 45 % causes a decrease of approximately 4%. The trend of the produced speed in foggy conditions provides additional support to the hypothesis that the speed estimate of forward translations is based on and biased towards the available velocity signals from the environment. In fact, an increment of the fog density reduces the visible areas to the closer regions where the retinal angular velocities are higher. We might then expect that the speed estimate is increased accordingly assuming a non-optimal compensation mechanism.

A common result that emerges from the three behavioral experiments presented so far (section 2.1, 2.3 and 2.4) is the general phenomenon of speed overproduction (underestimation) in simulated driving. The overproduction was about 30% in the first experiment and about 7-8% in the last two, executed in a different setup. We discuss this outcome in the section 4.2.3.

The common effect on produced speed found in all the experiments strengthens the result that the driving speed is decreased when driving in fog. As discussed previously, despite differences in the amount of contrast reduction, the extent of the field-of-view, the eye height, the training procedure and the driving setup this result has been confirmed in every experiment.

During the driving experiments we recorded several other performance measures in addition to the produced speed. Two of these measures were the trial duration and the traveled distance. For both of them we found no variations across the experimental conditions in the last two experiments (section 2.3 and 2.4). This result confirms that the visual cues (the ever-visible white road-edge lines) that we have implemented to allow the predictability of the path during fog were effective (Land & Lee, 1994; Land & Horwood, 1995). Although a higher standard deviation of the lateral shift has been measured when driving in fog, it seems reasonable to conclude that this countermeasure equalizes the difficulty of the trials, which can then be accomplished within the same time and distance range. In the first experiment, without these visual cues, the trial duration and the traveled distance were shorter when driving in fog. We have already discussed the possible reasons for these results in the section 2.5.2.2. A further result is that in clear visibility conditions drivers stay on average 11 cm to the left of the ideal centre of the lane, and in foggy conditions they drive even more to the left (18 cm), towards the central road markings that separate the two lanes.

In experiment 5 (section 2.6), the spatially uniform implementation of contrast reduction shows no effect on the perceived walking speed. When the reduction is applied either at the central region of the visual field or at the periphery, the linear speed is correctly estimated even with a contrast reduction up to 90%. The reason why we could not replicate the findings of our first psychophysical experiment are discussed in section 4.2.2.

In the experiment described in section 3.1 we have found that when the central region of the field-of-view is occluded the speed at the periphery is perceived as being higher. Conversely, when the periphery is masked the speed in the center is perceived as being lower than the speed of a reference scene that is fully visible. The dependence of the speed estimate of forward translation on the available velocity signals from the visible portion of the scene could explain the speed underproduction effect measured in fog. In fact, speed overestimation effect, caused by the masking of the central region of the field-of-view, has been measured at the perceptual level and seems to be the origin of the phenomenon. Furthermore, the central vision is certainly necessary and almost sufficient to correctly estimate the constant speed of forward self-motion in a driving simulation. Conversely, the influence of the peripheral region on the perceived speed seems to be less relevant, although still responsible for a bias (see paragraph 3.1.3). A further result indicate that a central field-of-view of 40 degrees is already sufficient to provide a correct speed estimate of forward self-motion in both a driving and a walking simulation (section 3.1 and 3.2).

In section 3.2 we essentially confirmed the results of the previous section. Even in the domain of the walking speed the pattern of perceived speed reflects the influence of retinal angular velocities, from both the center and the periphery of the field-of-view, on the self-speed estimation process. In the case of walking speed the results are even stronger, indicating that the central region is necessary and totally sufficient to correctly estimate the speed. On the other side, when the central area is visible, the additional information from the peripheral region seems to be irrelevant.

The results of section 3.3 show that when gazing centrally, i.e. reducing the declination angle, the perceived speed is lowered (higher PSE) than the speed perceived at a reference fixation angle. Accordingly, when gazing more peripherally the speed is perceived as being higher (lower PSE) if compared to the speed at the reference angle. This effect is enhanced in the limited FOV condition, suggesting that limiting the FOV impairs the compensation mechanism even more.

In the last experiment of this thesis, presented in section 3.4, we have shown that the optic flow coming from the road ahead strongly affects the produced speed, despite the presence of other motion cues in the periphery of the environment that provide a consistent information about the actual driving speed. This demonstrates the importance of the central portion of the scene and its dominant role for the estimation of the actual driving speed.

4.2. Discussions

4.2.1. Non-optimal compensation for retinal angular speeds

To interpret our results relatively to the effect of fog on perceived and produce speed we consider the *masking* effect of a gradient contrast reduction. Our stimuli for the driving simulation were rich and provided many visual cues for detecting motion. They presented motion parallax, induced by the road poles passing by, and texture with both low and high spatial frequencies (the surface of the road wall and the grass on the side hills, respectively) together with dashed road lines in the centre of the visual field, providing clear velocity signals. Even in the presence of many regular patterns in the environment, with the availability of temporal frequencies that were proportional to driving speed (since the spatial frequencies were not manipulated) we obtained a clear effect of the realistic contrast reduction.

A comparable effect was obtained by Dyre Schaudt and Lew (2005) who investigated in a psychophysical experiment the perception of speed with gradient contrast reduction (fog) and reported an increase in the perceived speed of approximately 5%, with a 67% increase in the fog density, whereas in our case the produced speed decreased by 8% with a contrast reduction of 57%. The stimuli used by Dyre, Shaudt and Lew (2005) consisted of computer simulations of observer translation, i.e. visual translations of a textured ground plane. The authors claimed that with a contrast gradient in depth, in which the contrast is reduced exponentially as distance increases, the re-sampling of the optic-flow enphasizes nearer objects and therefore, increases the rate of global optic-flow. Both the Global optic-flow rate (GOFR), i.e. the velocity of forward motion scaled to altitude units and the discontinuity rate, i.e. the passage of any arbitrary texture element through a fixed optical reference (Owen, Wolpert & Warren, 1984) have been shown to contribute to the perception of constant self-speed, with some dominance of the GOFR (Larish & Flach, 1990).

However, we rather argue that the perceived speed is altered directly by the retinal angular velocities coming from the visible portion of the scene. This assumption is motivated also by the results obtained in the experiment of section 2.4, where an increment of the fog density reduces the visible areas to the closer regions and the produced speed is decreased accordingly. This assumption is based on past findings (Morgan, 1980; Mkee & Nakayama, 1984; Snowden & Braddick, 1991) suggesting that the human visual system averages speed information to derive the mean. Watamaniuk and Duchon (1992) have clearly shown that the human visual system can extract the mean speed of a stimulus composed of many different speeds and use that information as the basis for speed discrimination (Figure 4.1).

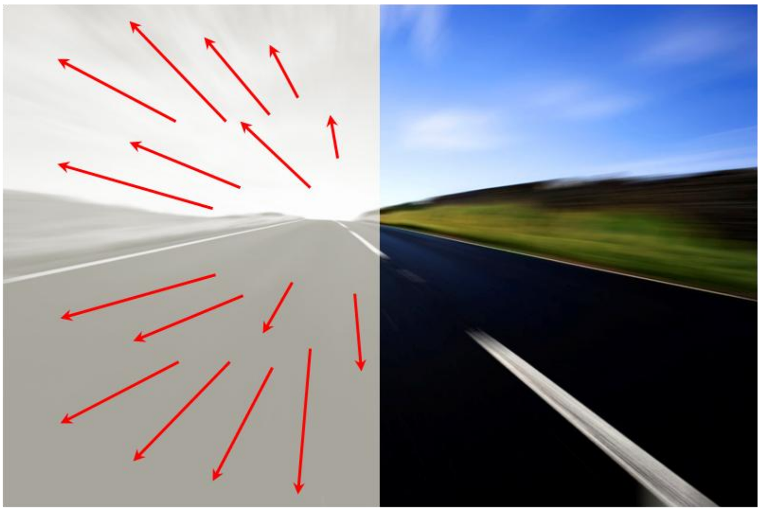

Figure 4.1: Optic-flow. In the radial expanding optic-flow pattern the velocity vectors change in speed and direction, but the subjective percept of an observer consists of a forward translation at constant speed. Local speeds are averaged across the visual field.

They speculated that the evaluation of the mean speed from a moving stimulus is used to reduce the noise of the signal and is analogous to perceiving a global mean direction when viewing a distribution of directions (Williams & Sekuler, 1984; Watamaniuk, Sekuler & Williams, 1989; Smith, Snowden & Milne, 1994).

However, an averaging of the angular velocity signals from the periphery of the visual field would produce a strong bias in the estimate of the self-speed of forward translation. In figure 3.9 we provide a representation of these biased values that one could expect in case the self-speed estimate would be based exclusively on the retinal angular velocities. We then hypothesize that a compensation mechanism weights the estimate from the angular velocities within the visible region of the field-of-view taking into account some visual cue from the scene. If the process were perfect, we could expect that, independently of the gaze direction and the extent of the field-of-view (section 3.3), the test speed would always be estimated correctly.

It has been shown that perfect velocity constancy can be achieved when perspective size, texture, viewing height, disparity, motion parallax cues and even familiarity with the object are combined (Distler, Gegenfurtner, van Veen, & Hawken, 2000). In this study the authors simulated translational object-motion combining those cues in a manner that mimics viewing in the natural environment. They argued that velocity constancy is achieved by scaling the retinal angular speed by the inter-object distances (relative depth).

Similarly, we propose that in order to account for the retinal angular velocities generated by self-motion, the depth of the environment must play a role in a hypothetical process where the different angular velocities are “compensated” and perceived as a single speed of translation in depth.

Bex, Metha and Makous (1998) suggested that, in speed discrimination task, the apparent speed of an optic-flow pattern depends on the configuration of the local motion that forms the pattern. Specifically, using annular patterns with the same spatial frequency

They asked observers to compare the apparent speed of drifting sinusoidal radial gratings (rings) to that of drifting sinusoidal translating gratings of the same spatial frequency. Along any radius of the radial grating, the spatial and temporal structure was identical to a horizontal radius of the translating grating. Although the radial grating did not have the true velocity gradient [i.e. the changes in velocity and spatial frequency with eccentricity] of an optic flow field, its spatial and temporal structure approximated optic flow accompanying self-motion or expansion of an object moving in depth. They found that radial patterns were perceived much (up to 60%) faster than translational patterns. They argued that the radial grating may appear to be moving in depth with respect to the observer and must travel a further distance in the same time (i.e., move faster), as shown in figure 4.2.

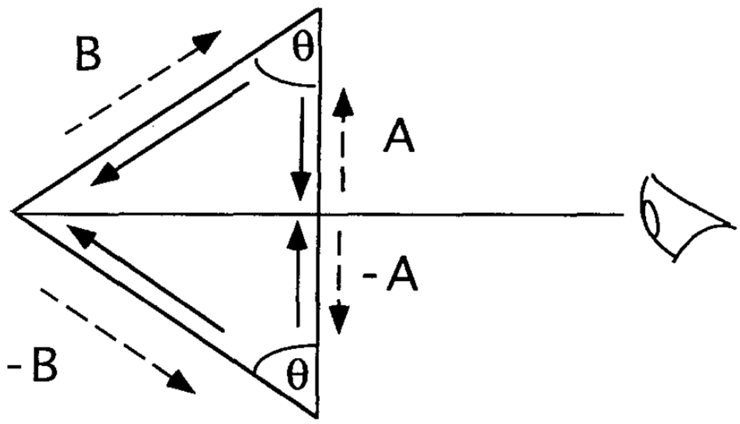

Figure 4.2: Perceived speed and direction of radial motion. An eye on the right of the figure observes local translational motion of speed A but motion is perceived in direction θ at speed B (from Bex and Makous, 1997).

Clifford, Beardsley and Vaina (1999) confirmed the findings of Bex and colleagues. They found that the results of perceived speed in complex motion are accounted for by a model satisfying simultaneous constraints on motion-in-depth and object rigidity.

From these observations we can derive that in a three-dimensional environment with a rigid structure the expanding radial pattern of optic-flow during forward self-motion contains changes in velocity and spatial frequencies that provide information about the depth. This information is not present in the translational component of the optic-flow, which happens to be the prevailing pattern in the periphery of the visual field, depicted by the closer regions of the environment. In other words, the radial component of the optic-flow is associated with distance from the observer. We believe that this type of information, together with the other distance visual cues described by Distler and colleagues (2000), is taken into account in order to compensate the changes with eccentricity (gradient) of the retinal angular velocities and to obtain a single speed estimate of forward self-motion. This information might be lost when the fog masks the distal region of the visual field, from where the radial component of the optic-flow mostly originates. This loss would be responsible for the non-optimal compensation that we have measured in or experiments and that we have show to depend on gaze direction and extent of the available field-of-view (section 3.3).

4.2.2. The inefficiency of the uniform contrast reduction

Starting point was a replication with more realistic implementation of contrast reduction of the experiment by Snowden, Stimpson and Ruddle (1998). They reported an increased produced speed as a consequence of a decreased perceived speed in a driving simulation with a spatially uniform contrast reduction. We could observe an effect of the spatially uniform contrast reduction on the perceived speed only in one experiment (section 2.2).

There are several possible explanations to account for the fact that such an effect has not been replicated afterwards. First, considering the technical differences between the two experimental setups used in our studies notable differences exist in the size and geometry of the field-of-view. The huge surface of the Panolab setup allows the projection of an image onto the peripheral visual field, which is normally not reached by standard visualization technologies, even in immersive virtual environments systems. The easiest explanation would be to assume that peripheral vision is not particularly sensitive to contrast. In one of our experiments (section 2.6) we have tested the hypothesis based on this assumption and compared directly the perceived speed in central and peripheral regions at different contrast levels. Our results allow us to exclude different sensitivities between the center and the periphery of the visual field.

The richness of our environment, in terms of visual cues for motion, might have played a role in the peripheral portion of the field-of-view, providing a strong stimulation for the detection and discrimination of speed. Such stimulation could have overcome the influence of a reduced contrast. This explanation is not in conflict with the psychophysical results from McKee, Silverman and Nakayama (1986), in which it has been shown that precise velocity discriminations are possible even at very low contrast.

On the level of a pure speculation we can propose a third explanation for the inefficiency, which can be linked to the *contrast normalization* that refers to an adaptation to the range of intensities (Gaudry & Reinagel, 2007; Schwartz & Simoncelli, 2001). This approach accounts for the changes in neuronal sensitivity for large differences at high contrast while remaining sensitive to small differences at low contrast, in order to code the large dynamic range of natural stimuli. We can reasonably assume that the study by Snowden and colleagues (1998), which found a strong effect of the uniform contrast reduction on the perceived and produced speed in a driving simulation, was executed using a visualization system with a relative small field-of-view. This implicates that a large portion of the visual field is stimulated by the background, i.e. the real environment. We need also to assume that the visual system *normalizes* the sensitivity to contrast taking into account the range of stimulation from within the whole visual field.

In case of contrast manipulation displayed within a small field-of-view, the contrast normalization would lead the visual system to tune the contrast sensitivity for a still wide range of variations, since the local contrast limited by the visualization system within a restricted field-of-view would hardly match the overall contrast produced also by the surrounding ambient light. In other words, with a similar setup the contrast sensitivity of the observer can detect only great variations of contrast. Therefore, when a small contrast reduction (compared to the overall contrast) is applied within a small portion of the visual field, the observer's ability to estimate speeds is impaired because the visual system cannot distinguish between the different levels of contrast.

In our setup, where the projection screen covers almost the entire visual field, the visual system normalizes the contrast sensitivity for a small range of contrast variation, i.e. within the range displayed by the visualization system. Therefore, we might expect that when the contrast of the virtual environment is decreased, the fine-tuning for small variations allows the visual system to easily distinguish between different speeds. Therefore the observer is able to accomplish the driving task for any specific target speed. We are going to study experimentally this hypothesis in the next future by simulating a small field-of-view and a corresponding background in our projection system.

4.2.3. General speed underestimation

The perception of speed in real and simulated environments is an issue that is being investigated for many years. In discussing the relationship between perceptual requirements and real-time graphics, Deyo, Briggs, and Doenges (1988) noted that "Driving involves very low eye heights where optical flow density must change very rapidly over the field of vision available from a car. The driver must be able to judge speed and proximity to obstacles very quickly by visualizing textural cues in and around the road as well as passing 3D features" (p. 320).

Among studies performed in real driving conditions is Denton's (1966) research, where a scale of subjective speed was obtained. Evans (1970), Ohta and Komatsu

(1991) investigated the effect of suppression of auditory or visual information on speed perception. Triggs and Berenyi (1982) and Osaka (1988) studied speed estimation under daylight and nighttime conditions. Recarte and Nunes (1996) investigated the equivalence of estimation and production methods. Considering the results of these researches, there is general agreement about the tendency to underestimate speed, depending on a diversity of experimental conditions. Recarte and Nunes (1996) proved the equivalence of the estimation and production methods and found a pattern of general underestimation and overproduction.

Despite the advances of technology simulation, the speed underestimation is reported also in driving simulation studies (Salvatore, 1969; Snowden *et al*., 1998; Rudin-Brown, 2006).

However, in our experiments the general speed underestimation (and overproduction) is reduced when the driving simulation is carried out using a large projection screen that surrounds the driver. In the first experiment we used a projection screen that covers 75 degrees of horizontal file-of-view and we measured a speed overproduction by 30%. In the following experiments we employed a semi-spherical screen with 230 degrees of horizontal field-of-view and the measured speed exceeded the target by no more than 8%. This result confirms the findings of previous studies about the effect of reduced field-of-view on speed perception (Salvatore, 1968; Osaka, 1988; Conchillo *at al.*, 1997).

We believe that this small speed underestimation, which remains left over from the valuable effect of enhanced screen size, might come from the absence of other sensory cues like auditory, vestibular and proprioceptive stimulations that are missing in our driving simulations (Kemeny & Panerai, 2003).

4.3. Conclusion

Our work shows that a realistic attenuation of contrast applied in a three-dimensional environment leads to an overestimation of the speed of self-motion. This bias in the perceived speed induces the moving observer to slow down.

Our results rule out the explanations provided so far for many psychophysical results in two-dimensional motion perception in which contrast reduction decreases the perceived speed of moving patterns. The implementation of a type of image contrast reduction that does not consider the distribution in depth of the real environment appears uniformly distributed all over the field-of-view and shows no effects on the perceived speed when applied to our stimuli. We hypothesize that the richness of the virtual environments used in our simulations or a more general phenomenon of contrast normalization occurred in the experimental room might explain the absence of these results.

The simulation of self-motion implies fundamental differences with respect to the classical psychophysical stimuli used for studying object-motion. When an observer is moving straight through the environment the structure of the visual scene induces a pattern of expanding radial optic-flow in the retina. Distal regions of the environment fall centrally in the visual field, whereas the proximal regions are projected in the periphery. The retinal angular velocities depicted by a forward translation of the observer show a positive gradient of speeds, meaning that the central portion of the visual field contains low velocity signals and the periphery contains high velocity signals. The human visual system is thought to average the speed information available in the image where many different speeds are present and derive the mean in order to use it for speed estimation.

When the contrast of the scene falls gradually according to the distance from the observer, like in fog, the velocity signals from the central portion of the visual field are masked. Therefore one can assume that the average speed retrieved from the available high velocity signals in the periphery would bias the estimate of the speed of self-motion towards higher values. We show also that as the fog density increases, therefore reducing the extent of the visible area to closer regions, the produced speed is decreased accordingly. This provides support to the explanation that the speed estimation process is biased towards the average speeds from the visible region of the environment. Our results show that the retinal angular velocities are only slightly biasing. We must assume that in the visual system a mechanism compensates for the speed gradient of the retinal angular velocities depicted by the visible regions of the scene in order to produce a percept of unique speed of forward translation. We speculate that this mechanism takes into account the pattern of radial motion from the expanding optic-flow to retrieve information about the depth of the environment. The reduced visibility of the distant regions of the environment due to contrast attenuation reduces the availability of the information about depth and causes a non-optimal compensation.

References

Adelson, E. H., & Bergen, J. R. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America. A, Optics and image science*, *2*, 284-99.

Adelson, E. H., & Movshon, J. A. (1982). Phenomenal coherence of moving visual patterns. *Nature*, *300*, 523-5.

Albright, T. D., & Stoner, G. R. (1995). Visual motion perception. *Proceedings of the National Academy of Sciences of the United States of America*, *92*, 2433-40.

Anderson, S. J., & Burr, D. C. (1991). Spatial summation properties of directionally selective mechanisms in human vision. *Journal of the Optical Society of America. A, Optics and image science, 8*, 1330-9.

Anderson, S. J., Burr, D. C., & Morrone, M. C. (1991). Two-dimensional spatial and spatial-frequency selectivity of motion-sensitive mechanisms in human vision. *Journal of the Optical Society of America. A, Optics and image science*, *8*, 1340-51.

Anstis, S. (2003). Moving objects appear to slow down at low contrasts. *Neural Networks*, *16*, 933-938.

Ascher, D., & Grzywacz, N. M. (2000). A bayesian model for the measurement of visual velocity. *Vision research*, *40*, 3427-34.

Banton, T., Stefanucci, J., Durgin, F., Fass, A., & Proffitt, D. (2005). The perception of walking speed in a virtual environment. *Presence: Teleoper. Virtual Environ*, *14*, 394-406.

Bardy, B. G., Warren, W. H., & Kay, B. A. (1999). The role of central and peripheral vision in postural control during walking. *Perception & psychophysics*, *61*, 1356-68.

Barfield, W., Rosenberg, C., & Furness TA 3rd. (1995). Situation awareness as a function of frame of reference, computer-graphics eyepoint elevation, and geometric field of view. *The International journal of aviation psychology*, *5*, 233-56.

Barlow, H. B., & Hill, R. M. (1963). Evidence for a Psysiological Explanation of the Waterfall Phenomenon and Figural After-Effects. *Nature*, *200*, 1345-7.

Bartmann, A., Spijkers, W., & Hess, M. (1991). Street environment, driving speed and field of vision. In *Vision in Vehicles III*. Amsterdam.

Baumberger, B., Fluckiger, M., & Roland, M. (2000). Walking in an environment of moving ground texture. *Japanese Psychological Research*, *42*, 238-250. doi: doi:10.1111/1468-5884.00151

Beardsley, S. A., & Vaina, L. M. (1998). Computational modelling of optic flow selectivity in MSTd neurons. *Network (Bristol, England)*, *9*, 467-93.

Beardsley, S. A., & Vaina, L. M. (2005). Psychophysical evidence for a radial motion bias in complex motion discrimination. *Vision research*, *45*, 1569-86.

Benton, C. P., & Johnston, A. (2001). A new approach to analysing texture-defined motion. *Proceedings. Biological sciences / The Royal Society*, *268*, 2435-43.

Benton, C. P. (2002). Gradient-based analysis of non-Fourier motion. *Vision research*, *42*, 2869-77.

Berthoz, A., Jeannerod, M., Vital-Durand, F., & Oliveras, J. L. (1975). Development of vestibulo-ocular responses in visually deprived kittens. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *23*, 425-42.

Berthoz, A., Pavard, B., & Young, L. R. (1975a). Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *23*, 471-89.

Berthoz, A., Pavard, B., & Young, L. R. (1975b). Perception of linear horizontal self-motion induced by peripheral vision (linearvection) basic characteristics and visual-vestibular interactions. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *23*, 471-89.

Bex, P. J., Metha, A. B., & Makous, W. (1998). Psychophysical evidence for a functional hierarchy of motion processing mechanisms. *Journal of the Optical Society of America. A, Optics, image science, and vision*, *15*, 769-76.

Bex, P. J., & Makous, W. (1997). Radial motion looks faster. *Vision Research*, *37*, 3399-3405.

Bex, P. J., Metha, A. B., & Makous, W. (1999). Enhanced motion aftereffect for complex motions. *Vision Research*, *39*, 2229-2238.

Biocca, F., & Delaney, B. (1995). Immersive virtual reality technology. In *Communication in the Age of Virtual Reality* (pp. 57-124). Hillsdale NJ: Lawrence Erlbaum Associates.

Blakemore, M. R., & Snowden, R. J. (1999). The effect of contrast upon perceived speed: a general phenomenon? *Perception*, *28*, 33-48.

Blakemore, M. R., & Snowden, R. J. (2000). Textured backgrounds alter perceived speed. *Vision research*, *40*, 629-38.

Brandt, Dichgans, & Koenig. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research, 16,* 476-491. doi: 10.1007/BF00234474

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of central verses peripheral vision on egocentric and exocentric motion perception. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale, 16,* 476-91.

Brookhuis, Volkerts, & O'Hanlon. (1990). Repeated dose effects of lormetazepam and flurazepam upon driving performance. *European Journal of Clinical Pharmacology, 39,* 83-87. doi: 10.1007/BF02657065

Brookhuis, K. A., Vries, G. D., & Waard, D. D. (1993). Acute and subchronic effects of the H1-histamine receptor antagonist ebastine in 10, 20 and 30 mg dose, and triprolidine 10 mg on car driving performance. *British Journal of Clinical Pharmacology, 36.*

Brooks, K. (2001). Stereomotion speed perception is contrast dependent. *Perception, 30,* 725-31.

Bruggeman, H., Zosh, W., & Warren, W. H. (2007). Optic flow drives human visuo-locomotor adaptation. *Current biology : CB, 17,* 2035-40.

Casey, S. M., & Lund, A. K. (1987). Three field studies of driver speed adaptation. *Human factors, 29,* 541-550.

Champion, R. A., Hammett, S. T., & Thompson, P. G. (2007). Perceived direction of plaid motion is not predicted by component speeds. *Vision research, 47,* 375-83.

Clifford, C. W., Beardsley, S. A., & Vaina, L. M. (1999). The perception and discrimination of speed in complex motion. *Vision research, 39,* 2213-27.

Conchillo, A., Nunes, L., Ruiz, T., & Recarte, M. A. (1997). Effect of the retinal size and peripheral field restriction on speed perception of an automobile in a video scene. In *Vision in Vehicles VII* (pp. 93-100). Amsterdam: Elsevier Science.

Conchillo, A., Recarte, M. A., Nunes, L., & Ruiz, T. (2006a). Comparing speed estimations from a moving vehicle in different traffic scenarios: absence versus presence of traffic flow. *The Spanish journal of psychology*, *9*, 32-7.

Conchillo, A., Recarte, M. A., Nunes, L., & Ruiz, T. (2006b). Comparing speed estimations from a moving vehicle in different traffic scenarios: absence versus presence of traffic flow. *The Spanish journal of psychology*, *9*, 32-7.

Cox, E. M., & Dyre, B. P. Control of Egospeed: Influence of Discontinuity Rate and Global Optical Flow Rate.

Crowell, J. A., & Banks, M. S. (1993). Perceiving heading with different retinal regions and types of optic flow. *Perception & psychophysics*, *53*, 325-37.

Cruz-Neira, C., Sandin, D. J., & DeFanti, T. A. (1993). Surround-screen projection-based virtual reality: the design and implementation of the CAVE. *Proceedings of the 20th annual conference on Computer graphics and interactive techniques*, 135-142.

Culham, J., He, S., Dukelow, S., & Verstraten, F. A. (2001). Visual motion and the human brain: what has neuroimaging told us? *Acta psychologica*, *107*, 69-94.

Culham, J. C., Verstraten, F. A., Ashida, H., & Cavanagh, P. (2000). Independent aftereffects of attention and motion. *Neuron*, *28*, 607-15.

Cutting, J. E., Springer, K., Braren, P. A., & Johnson, S. H. (1992). Wayfinding on Foot From Information in Retinal, Not Optical, Flow. *Journal of Experimental Psychology: General*, *121*, 41-72.

Cynader, M., & Regan, D. (1978). Neurones in cat parastriate cortex sensitive to the direction of motion in three-dimensional space. *The Journal of physiology*, *274*, 549-69.

Durgin, F. H., Gigone, K. & Scott, R., (2005). Perception of visual speed while moving. *Journal of Experimental Psychology: Human Perception and*

Performance, *31*, 339-353.

De Valois, K. K., & Switkes, E. (1980). Spatial frequency specific interaction of dot patterns and gratings. *Proceedings of the National Academy of Sciences of the United States of America*, *77*, 662-5.

Del Viva, M. M., & Morrone, M. C. (1998). Motion analysis by feature tracking. *Vision research*, *38*, 3633-53.

Denton, G. G. (1980). A Subjective Scale of Speed when Driving a Motor Vehicle.

Derrington, A. M., & Badcock, D. R. (1992). Two-stage analysis of the motion of 2-dimensional patterns, what is the first stage? *Vision research*, *32*, 691-8.

Derrington, A. M., Lennie, P., & Wright, M. J. (1979). The mechanism of peripherally evoked responses in retinal ganglion cells. *The Journal of physiology*, *289*, 299-310.

Derrington, A. M., Allen, H. A., & Delicato, L. S. (2004). Visual mechanisms of motion analysis and motion perception. *Annual review of psychology*, *55*, 181-205.

Deyo, R., Briggs, J. A., & Doenges, P. (1988). Getting graphics in gear: graphics and dynamics in driving simulation. *SIGGRAPH Comput. Graph*, *22*, 317-326.

Dichgans, J., & Brandt, T. (1978). *Handbook of sensory physiology* (Held, H.W. Leibowitz and H.L. Teuber). Heidelberg: Springer.

Distler, H. K., & Buelthoff, H. H. (1996). Velocity perception in 3D environments. *Perception*, *25 ECVP Abstract Supplement*.

Distler, H. K., Gegenfurtner, K. R., van Veen, H. A., & Hawken, M. J. (2000). Velocity constancy in a virtual reality environment. *Perception*, *29*, 1423-35.

van Doorn, A. J., Koenderink, J. J., & van de Grind, W. A. (1985). Perception of movement and correlation in stroboscopically presented noise patterns. *Perception*, *14*, 209-24.

Duffy, C. J., & Wurtz, R. H. (1991a). Sensitivity of MST neurons to optic flow stimuli. I. A continuum of response selectivity to large-field stimuli. *Journal of neurophysiology*, *65*, 1329-45.

Duffy, C. J., & Wurtz, R. H. (1991b). Sensitivity of MST neurons to optic flow stimuli. II. Mechanisms of response selectivity revealed by small-field stimuli. *Journal of neurophysiology*, *65*, 1346-59.

Durgin, F., Gigone, K., & Scott, R. (2005). Perception of visual speed while moving. *Journal of Experimental Psychology: Human Perception and Performance*, *31*, 339-53.

Durlach, N. I., & Mavor, A. S. (1995). *Virtual reality: Scientific and Technological challenges*. Washington, DC: National Academy Press.

Dyre, B. P., Schaudt, W. A., & Lew, R. T. (2005). Contrast gradients increase apparent egospeed while moving through simulated fog [Abstract]. *Journal of Vision*, *5*, 335.

Edwards, M., & Badcock, D. R. (1993). Asymmetries in the sensitivity to motion in depth: a centripetal bias. *Perception*, *22*, 1013-23.

Edwards, M., & Ibbotson, M. R. (2007). Relative sensitivities to large-field optic-flow patterns varying in direction and speed. *Perception*, *36*, 113-24.

Ellis, S. R. Origins and elements of virtual environments.

Ellis, S. R. (1995). Origins and elements of virtual environments. In *Virtual environments and avanced interface design* (pp. 14-57). New York: Oxford University Press.

Epstein, W., & Cody, W. J. (1980). Perception of relative velocity: a revision of the hypothesis of relational determination. *Perception*, *9*, 47-60.

Epstein, W. (1965). Perceptual Invariance in the Kinetic Depth-Effect. *The American Journal of Psychology*, *78*, 301-303.

van Erp, J. B. F., & Padmos, P. (2003). Image parameters for driving with indirect viewing systems. *Ergonomics*, *46*, 1471-99.

Evans, L. (1991). Airbag effectiveness in preventing fatalities predicted according to type of crash, driver age, and blood alcohol concentration. *Accident; analysis and prevention*, *23*, 531-41.

Felleman, D. J., & Van Essen, D. C. (1987). Receptive field properties of neurons in area V3 of macaque monkey extrastriate cortex. *Journal of neurophysiology*, *57*, 889-920.

Fennema, C. L., & Thompson, W. B. (1979). Velocity determination in scenes containing several moving objects. *Computer Graphics and Image Processing*, *9*, 301-315.

Ferrera, V. P., & Wilson, H. R. (1987). Direction specific masking and the analysis of motion in two dimensions. *Vision research*, *27*, 1783-96.

Fildes, B., & Lee, S. (1993). The Speed Review: Road Environment, Behaviour, Speed Limits, Enforcement and Crashes. Federal Office of Road Safety, Report CR127, Department of Transport and Communications, Canberra.

Flach, J. M., Junaid, A. A., & Warren, R. Judgments of Speed of Self-Motion: Modeling the Relative Effects of Speed and Altitude Change.

Flückiger, M., & Baumberger, B. (1988). The perception of an optical flow projected on the ground surface. *Perception*, *17*, 633-45.

Foster, K. H., Gaska, J. P., Nagler, M., & Pollen, D. A. (1985). Spatial and temporal frequency selectivity of neurones in visual cortical areas V1 and V2 of the macaque monkey. *The Journal of physiology*, *365*, 331-63.

Freeman, T. C., & Harris, M. G. (1992). Human sensitivity to expanding and rotating motion: effects of complementary masking and directional structure. *Vision Research*, *32*, 81-87.

Gaudry, K. S., & Reinagel, P. (2007). Benefits of contrast normalization demonstrated in neurons and model cells. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *27*, 8071-9.

Geesaman, B. J., & Qian, N. (1996). A novel speed illusion involving expansion and rotation patterns. *Vision research*, *36*, 3281-92.

Geesaman, B. J., & Qian, N. (1998). The effect of complex motion pattern on speed perception. *Vision research*, *38*, 1223-31.

Gegenfurtner, K. R., Mayser, H., & Sharpe, L. T. (1999). Seeing movement in the dark. *Nature*, *398*, 475-6.

Gibson, J. J. (1950). *Perception of the Visual World*. Boston: Houghton Mifflin.

Graziano, M. S., Yap, G. S., & Gross, C. G. (1994). Coding of visual space by premotor neurons. *Science (New York, N.Y.)*, *266*, 1054-7.

Green, P., Lin, B., & Bagian, T. (1993). Effect of Road Geometry on Driving Workload: A Pilot Experiment (Technical Report UMTRI-93-39, GLCTTR 22-91/01), Ann Arbor, MI: The University of Michigan Transportation Research Institute.

van de Grind, W. A., Koenderink, J. J., & van Doorn, A. J. (1986). The distribution of human motion detector properties in the monocular visual field. *Vision research*, *26*, 797-810.

van de Grind, W. A., Koenderink, J. J., & van Doorn, A. J. (1987). Influence of contrast on foveal and peripheral detection of coherent motion in moving random-dot pattterns. *Journal of the Optical Society of America*, *4*, 1643-1652.

van de Grind, W. A., Koenderink, J. J., & van Doorn, A. J. (2000). Motion detection from photopic to low scotopic luminance levels. *Vision research*, *40*, 187-99.

Grzywacz, N. M., & Yuille, A. L. (1990). A model for the estimate of local image velocity by cells in the visual cortex. *Proceedings of the Royal Society of London. Series B, Containing papers of a Biological character. Royal Society (Great Britain)*, *239*, 129-61.

Grzywacz, N. M., Watamaniuk, S. N., & Mckee, S. P. (1995). Temporal coherence theory for the detection and measurement of visual motion. *Vision Research*, *35*, 3183-3203.

Haag, J., Denk, W., & Borst, A. (2004). Fly motion vision is based on Reichardt detectors regardless of the signal-to-noise ratio. *Proceedings of the National Academy of Sciences of the United States of America*, *101*, 16333-8.

Habak, C., Casanova, C., & Faubert, J. (2002). Central and peripheral interactions in the perception of optic flow. *Vision research*, *42*, 2843-52.

Hammett, S. T., Thompson, P. G., & Bedingham, S. (2000). The dynamics of velocity adaptation in human vision. *Current biology : CB*, *10*, 1123-6.

Hammett, S. T., Champion, R. A., Morland, A. B., & Thompson, P. G. (2005). A ratio model of perceived speed in the human visual system. *Proceedings. Biological sciences / The Royal Society*, *272*, 2351-6.

Hammett, S. T., Champion, R. A., Thompson, P. G., & Morland, A. B. (2007). Perceptual distortions of speed at low luminance: evidence inconsistent with a Bayesian account of speed encoding. *Vision research*, *47*, 564-8.

Harris, M. (1986). The perception of moving stimuli: A model of spatiotemporal coding in human vision. *Vision Research*, *26*, 1281-1287.

Hawken, M. J., Gegenfurtner, K. R., & Tang, C. (1994). Contrast dependence of colour and luminance motion mechanisms in human vision. *Nature*, *367*, 268-70.

Heeger, D. J. (1987a). Model for the extraction of image flow. *Journal of the Optical Society of America. A, Optics and image science*, *4*, 1455-71.

Heeger, D. J. (1987b). Model for the extraction of image flow. *Journal of the Optical Society of America. A, Optics and image science*, *4*, 1455-71.

von Helmholtz, H. (1924). *Treatise on physiological optics* (J. P. C. Southall). Ithaca: Optical Society of America.

Hogervorst, M. A., Glennerster, A., & Eagle, R. A. (2003). Pooling speed information in complex tasks: Estimation of average speed and detection of nonplanarity. *Journal of Vision*, *3*, 464-485.

Horberry, T., Anderson, J., & Regan, M. A. (2006). The possible safety benefits of enhanced road markings: A driving simulator evaluation. *Transportation Research Part F: Traffic Psychology and Behaviour*, *9*, 77-87.

Hubel, D. H., & Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *The Journal of physiology*, *195*, 215-43.

Hubel, D. H., & Wiesel, T. N. (1977). Ferrier lecture. Functional architecture of macaque monkey visual cortex. *Proceedings of the Royal Society of London. Series B, Containing papers of a Biological character. Royal Society (Great Britain)*, *198*, 1-59.

Hürlimann, F., Kiper, D. C., & Carandini, M. (2002). Testing the Bayesian model of perceived speed. *Vision research*, *42*, 2253-7.

Jia, Z., Jia, Z., & Balasuriya, A. (2005). Motion Based Image Segmentation with Unsupervised Bayesian Learning. *Motion and Video Computing, 2005. WACV/MOTIONS '05 Volume 2. IEEE Workshop on*, *2*, 2-7.

Johnston, A., McOwan, P. W., & Buxton, H. (1992). A computational model of the analysis of some first-order and second-order motion patterns by simple and complex cells. *Proceedings. Biological sciences / The Royal Society*, *250*, 297-306.

Kaiser, M. K., & Hecht, H. (1995). Time-to-passage judgments in nonconstant optical flow fields. *Perception and Psychophysics*, *57*, 817-825.

Kalawsky, R. S. (1993). *The Science of Virtual Reality and Virtual Environments*. Wokingham: Addison-Wesley.

Kemeny, A., & Panerai, F. (2003). Evaluating perception in driving simulation experiments. *Trends Cogn Sci*, *7*, 31-37.

Khuu, S. K., & Badcock, D. R. (2002). Global speed processing: evidence for local averaging within, but not across two speed ranges. *Vision research*, *42*, 3031-42.

Kleinschmidt, A., Thilo, K. V., Büchel, C., Gresty, M. A., Bronstein, A. M., & Frackowiak, R. S. J. (2002). Neural correlates of visual-motion perception as object- or self-motion. *NeuroImage*, *16*, 873-82.

Koenderink, J. J. (1986). Optic flow. *Vision research*, *26*, 161-79.

Koenderink, J. J., & van Doorn, A. J. (1986a). Dynamic shape. *Biological cybernetics*, *53*, 383-96.

Koenderink, J. J., & van Doorn, A. J. (1986b). Depth and shape from differential perspective in the presence of bending deformations. *Journal of the Optical Society of America. A, Optics and image science*, *3*, 242-9.

Koffka, K. (1935). *Principles of Gestalt Psychology* (1 edition). New York: Harcourt.

Kontsevich, L. L., & Tyler, C. W. (1999). Bayesian adaptive estimation of psychometric slope and threshold. *Vision research*, *39*, 2729-37.

Koschmieder, H. (1924). Theorie der horizontalen Sichweite. *Beitr. Phys. Freien Atmos.*, *12*, 33-53; 171-181.

Land, M. F., & Lee, D. N. (1994a). Where we look when we steer. *Nature*, *369*, 742-744. doi: 10.1038/369742a0

Land, M. F., & Lee, D. N. (1994b). Where we look when we steer. *Nature*, *369*, 742-744. doi: 10.1038/369742a0

Land, M., & Horwood, J. (1995). Which parts of the road guide steering? *Nature*, *377*, 339-340. doi: 10.1038/377339a0

Lankheet, M. J. M., van Doorn, A. J., Bouman, M. A., & van de Grind, W. A. (2000). Motion coherence detection as a function of luminance level in human central vision. *Vision Research*, *40*, 3599-3611.

Lappe, Bremmer, & van den Berg AV. (1999). Perception of self-motion from visual flow. *Trends Cogn Sci*, *3*, 329-336.

Lappe, M., & Duffy, C. J. (1999). Optic flow illusion and single neuron behaviour reconciled by a population model. *The European journal of neuroscience*, *11*, 2323-31.

Lappe, M., & Rauschecker, J. P. (1994). Heading detection from optic flow. *Nature*, *369*, 712-3.

Lappe, M., & Rauschecker, J. P. (1995a). Motion anisotropies and heading detection. *Biological cybernetics*, *72*, 261-77.

Lappe, M., & Rauschecker, J. P. (1995b). An illusory transformation in a model of optic flow processing. *Vision research*, *35*, 1619-31.

Larisch, J. F., & Flach, J. M. (1990). Sources of optical information useful for perception of speed of rectilinear self-motion. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 295-302.

Lee, D. N. (1976). A theory of visual control of braking based on information about time-to-collision. *Perception, 5*, 437-59.

Lee, W. A. (1980). Anticipatory control of postural and task muscles during rapid arm flexion. *Journl of Motor Behavior, 12*, 185-196.

Lenne, M. G., Dietze, P., Rumbold, G. R., Redman, J. R., & Triggs, T. J. (2003). The effects of the opioid pharmacotherapies methadone, LAAM and buprenorphine, alone and in combination with alcohol, on simulated driving. *Drug and Alcohol Dependence*, *72*, 271-278.

Levitt, H. (1971). Transformed up-down methods in psychoacoustics. *Journal of Acustical Society of America*, *49*, 467-477.

Logothetis, N. K. (1999). Vision: a window on consciousness. *Scientific American*, *281*, 69-75.

Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior research methods, instruments, & computers : a journal of the Psychonomic Society, Inc*, *31*, 557-64.

Lorenceau, J. (1998). Veridical perception of global motion from disparate component motions. *Vision research*, *38*, 1605-10.

Lu, Z. L., & Sperling, G. (1995a). Attention-generated apparent motion. *Nature*, *377*, 237-9.

Lu, Z. L., & Sperling, G. (1995b). The functional architecture of human visual motion perception. *Vision research*, *35*, 2697-722.

Lu, Z. L., & Sperling, G. (2001). Three-systems theory of human visual motion perception: review and update. *Journal of the Optical Society of America. A, Optics, image science, and vision*, *18*, 2331-70.

Mather, G. (1988). Temporal properties of apparent motion in subjective figures. *Perception*, *17*, 729-36.

Maunsell, J. H., & van Essen, D. C. (1983). The connections of the middle temporal visual area (MT) and their relationship to a cortical hierarchy in the macaque monkey. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *3*, 2563-86.

Maunsell, J. H., & Van Essen, D. C. (1983a). Functional properties of neurons in middle temporal visual area of the macaque monkey. I. Selectivity for stimulus direction, speed, and orientation. *Journal of neurophysiology*, *49*, 1127-47.

Maunsell, J. H., & Van Essen, D. C. (1983b). Functional properties of neurons in middle temporal visual area of the macaque monkey. II. Binocular interactions and sensitivity to binocular disparity. *Journal of neurophysiology*, *49*, 1148-67.

McKee, S. P., & Nakayama, K. (1984). The detection of motion in the peripheral visual field. *Vision research*, *24*, 25-32.

McKee, S. P., Silverman, G. H., & Nakayama, K. (1986). Precise velocity discrimination despite random variations in temporal frequency and contrast. *Vision research*, *26*, 609-19.

McKee, S. P., & Welch, L. (1989). Is there a constancy for velocity? *Vision research*, *29*, 553-61.

Mingolla, E., & Todd, J. T. (1986). Perception of solid shape from shading. *Biological cybernetics*, *53*, 137-51.

Moradi, F., & Shimojo, S. (2004). Suppressive effect of sustained low-contrast adaptation followed by transient high-contrast on peripheral target detection. *Vision Research*, *44*, 449-460.

Morgan, M. J. (1980). Analogue models of motion perception. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, *290*, 117-35.

Morrone, M. C., Burr, D. C., Di Pietro, S., & Stefanelli, M. A. (1999). Cardinal directions for visual optic flow. *Current biology : CB*, *9*, 763-6.

Morrone, M. C., Burr, D. C., & Vaina, L. M. (1995). Two stages of visual processing for radial and circular motion. *Nature*, *376*, 507-9.

Moulden, B., Kingdom, F., & Gatley, L. F. (1990). The standard deviation of luminance as a metric for contrast in random-dot images. *Perception*, *19*, 79-101.

Movshon, J. A., Adelson, Gizzi, M. S., & Newsome, W. T. (1985). The analysis of moving visual patterns. In *Pattern Recognition Mechanisms* (pp. 117-151). Pontificiae Academiae Scientiarum Scripta Varia. Rome: Vatican Press.

Müller, R., & Greenlee, M. W. (1994a). Effect of contrast and adaptation on the perception of the direction and speed of drifting gratings. *Vision research*, *34*, 2071-92.

Müller, R., & Greenlee, M. W. (1994b). Effect of contrast and adaptation on the perception of the direction and speed of drifting gratings. *Vision research*, *34*, 2071-92.

Muller, R., & Greenlee, M. W. (1994). Effect of contrast and adaptation on the perception of the direction and speed of drifting gratings. *Vision Research*, *34*, 2071-2092.

Nakayama, K. (1985). Biological image motion processing: a review. *Vision research*, *25*, 625-60.

Nakayama, K., & Loomis, J. M. (1974). Optical velocity patterns, velocity-sensitive neurons, and space perception: a hypothesis. *Perception*, *3*, 63-80.

Ohta, H., & Komatsu, H. (1991). Speed perception in driving. Comparison with T.V. observation. In: A.G. Gale, I.D. Brown, C.M. Haslegrave, I. Moordhead and S. Taylor, Editors, Vision in vehicles Vol. II, North Holland, Amsterdam (1991). In *Vision in Vehicles II*. Amsterdam.

Orban, G. A., Lagae, L., Verri, A., Raiguel, S., Xiao, D., Maes, H., et al. (1992). First-order analysis of optical flow in monkey brain. *Proceedings of the National Academy of Sciences of the United States of America*, *89*, 2595-9.

Osaka, N. (1988). Speed estimation through restricted visual field during driving in day and night: naso-temporal hemifield differences. In *Vision in Vehicles II* (pp. 45-55). North-Holland: Elsevier Science.

Owen, D. H., Wolpert, L., & Warren, R. (1984). Effects of optical flow acceleration, edge acceleration and viewing time on the perception of egospeed acceleration.

Panerai, F. (2001). Speed and safety distance control in truck driving: comparison of simulation and real-world environment. *Proc. Driving Simulation Conf. DSC 2000*.

Perrone, J. A. (1992). Model for the computation of self-motion in biological systems. *Journal of the Optical Society of America*, *9*, 177-194.

Perrone, J. A. (2005). Economy of scale: a motion sensor with variable speed tuning. *Journal of vision*, *5*, 28-33.

Pretto, P., & Chatziastros, A. (2006a). Changes in optic-flow and scene contrast affect the driving speed. DSC 2006 Europe - Driving Simulation Conference, 263-272.

Pretto, P., & Chatziastros, A. (2006b). The role of scene contrast and optic-flow on driving speed. Vision in Vehicles XI.

Pretto, P., Vidal, M., & Chatziastros, A. (2008). Why fog increases the perceived speed. DSC 2008 Europe - Driving Simulation Conference.

Prokop, T., Schubert, M., & Berger, W. (1997). Visual influence on human locomotion. Modulation to changes in optic flow. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, *114*, 63-70.

Readinger, W. O., Chatziastros, A., Cunningham, D. W., & Buelthoff, H. H. (2001). Driving effects of retinal-flow properties associated with eccentric gaze. *Perception*, *30 ECVP Abstract Supplement*.

Recarte, M. A., & Nunes, L. (1996). Perception of Speed in an Automobile: Estimation and Production. *Journal of Experimental Psychology: Applied*, *2*, 291-304.

Regan, D., & Beverly, K. I. (1982). How do we avoid confounding the direction we are looking and the direction we are moving? *Science*, *215*, 194-196.

Regan, D., & Beverley, K. (1978). Looming detectors in the human visual pathway. *Vision Research*, *18*, 415-421.

Regan, D., & Beverley, K. (1983). Visual fields for frontal plane motion and for changing size. *Vision Research*, *23*, 673-676.

Reichardt, W. (1961). Autocorrelation, a principle for evaluation of sensory information by the central nervous system. In *Principles of Sensory Communications* (pp. 303-317). New York: John Wiley.

Reichardt, W., & Varju, D. (1959). [Transmission features in the evaluation system for optokinetics. (Conclusions from experiments on the beetle Chlorophanus viridis)]. *Zeitschrift für Naturforschung. Teil B: Chemie, Biochemie, Biophysik, Biologie*, *14B*, 674-89.

Rheingold, H. (1991). *Virtual Reality*. New York: Summit.

Rogers, B., & Koenderink, J. Monocular aniseikonia: a motion parallax analogue of the disparity-induced effect. *Nature*, *322*, 62-3.

Royden, C. S., Crowell, J. A., & Banks, M. S. (1994). Estimating heading during eye movements. *Vision research*, *34*, 3197-214.

Rudin-Brown, C. M. (2006). The effect of driver eye height on speed choice, lane-keeping, and car-following behavior: results of two driving simulator studies. *Traffic injury prevention*, *7*, 365-72.

Salvatore, S. (1968). The estimation of vehicular velocity as a function of visual stimulation. *Human factors*, *10*, 27-31.

Salvatore, S. (1969). Effect of removing acceleration cues on sensing vehicular velocity. *Perceptual and motor skills*, *28*, 615-22.

van Santen, J. P., & Sperling, G. (1984). Temporal covariance model of human motion perception. *Journal of the Optical Society of America. A, Optics and image science*, *1*, 451-73.

van Santen, J. P., & Sperling, G. (1985). Elaborated Reichardt detectors. *Journal of the Optical Society of America. A, Optics and image science*, *2*, 300-21.

Schiff, W., & Detwiler, M. L. (1979). Information used in judging impending collision. *Perception*, *8*, 647-58.

Schrater, P. R., Knill, D. C., & Simoncelli, E. P. (2001). Perceiving visual expansion without optic flow. *Nature*, *410*, 816-9.

Schwartz, O., & Simoncelli, E. P. (2001). Natural signal statistics and sensory gain control. *Nature neuroscience*, *4*, 819-25.

Shrivastava, A., Hayhoe, M. M., Pelz, J. B., & Mruczek, R. (2005). Influence of optic flow field restrictions and fog on perception of speed in a virtual driving environment [Abstract]. *Journal of Vision*, *5*, 139.

Smith, A. T., Snowden, R. J., & Milne, A. B. (1994). Is global motion really based on spatial integration of local motion signals? *Vision research*, *34*, 2425-30.

Smith, A., & Edgar, G. (1994). Antagonistic comparison of temporal frequency filter outputs as a basis for speed perception. *Vision Research*, *34*, 253-265.

Snowden, R. J., Stimpson, N., & Ruddle, R. A. (1998). Speed perception fogs up as visibility drops. *Nature*, *392*, 450.

Snowden, R. J., & Braddick, O. J. (1991). The temporal integration and resolution of velocity signals. *Vision Research*, *31*, 907-914.

Snowden, R. J., & Milne, A. B. (1997). Phantom motion aftereffects - evidence of detectors for the analysis of optic flow. *Current Biology*, *7*, 717-722.

Stocker, A. A., & Simoncelli, E. P. (2006). Noise characteristics and prior expectations in human visual speed perception. *Nature neuroscience*, *9*, 578-85.

Stone, L. S., & Thompson, P. (1992). Human speed perception is contrast dependent. *Vision Research*, *32*, 1535-1549.

Takeuchi, T., & De Valois, K. K. (2000). Velocity discrimination in scotopic vision. *Vision research*, *40*, 2011-24.

Tanaka, K., & Saito, H. (1989). Analysis of motion of the visual field by direction, expansion/contraction, and rotation cells clustered in the dorsal part of the medial superior temporal area of the macaque monkey. *Journal of Neurophysiology*, *62*, 626-641.

Thompson, P. (1982). Perceived rate of movement depends on contrast. *Vision research*, *22*, 377-80.

Thompson, P. G., Stone, L. S., & Brooks, K. (1995). Speed perception in the fovea is not always independent of contrast. *Perception*, *24*.

Thompson, P. (1981). Velocity after-effects: The effects of adaptation to moving stimuli on the perception of subsequently seen moving stimuli. *Vision Research*, *21*, 337-345.

Thompson, P., Brooks, K., & Hammett, S. T. (2006). Speed can go up as well as down at low contrast: implications for models of motion perception. *Vision research*, *46*, 782-6.

Tinsley, C. J., Webb, B. S., Barraclough, N. E., Vincent, C. J., Parker, A., & Derrington, A. M. (2003). The nature of V1 neural responses to 2D moving patterns depends on receptive-field structure in the marmoset monkey. *Journal of neurophysiology*, *90*, 930-7.

Todd, J. T. (1981). Visual information about moving objects. *Journal of Experimental Psychology: Human Perception and Performance*, *7*, 795-810.

Banton, Stefanucci, Durgin, Fass, & Proffitt. (2006). The Perception of Walking Speed in a Virtual Environment.

Tootell, R. B., Reppas, J. B., Dale, A. M., Look, R. B., Sereno, M. I., Malach, R., et al. (1995). Visual motion aftereffect in human cortical area MT revealed by functional magnetic resonance imaging. *Nature*, *375*, 139-41.

Triggs, T. J., & Berenyi, J. S. (1982). Estimation of automobile speed under day and night conditions. *Human factors*, *24*, 111–114.

Ullman, S. (1979). The interpretation of structure from motion. *Proceedings of the Royal Society of London. Series B, Containing papers of a Biological character. Royal Society (Great Britain)*, *203*, 405-26.

Ullman, S. (1986). The optical flow of planar surfaces. *Spatial vision*, *1*, 263-76.

Uttal, W. R., Spillmann, L., Sturzel, F., & Sekuler, A. B. (2000). Motion and shape in common fate. *Vision Research*, *40*, 301-310.

Wallach, H., & O'Connell, D. N. (1953). The kinetic depth effect. *Journal of experimental psychology*, *45*, 205-17.

Wallach, H., O'Connell, D. N., & Neisser, U. (1953). The memory effect of visual perception of three-dimensional form. *Journal of experimental psychology*, *45*, 360-8.

Warren, W. H., & Hannon, D. J. (1988). Direction of selfmotion is perceived from optical flow. *Nature*, *336*, 162-163.

Warren, W. H., & Kurtz, K. J. (1992). The role of central and peripheral vision in perceiving the direction of self-motion. *Perception & psychophysics*, *51*, 443-54.

Warren, W. H., Morris, M. W., & Kalish, M. (1988). Perception of translational heading from optical flow. *Journal of experimental psychology. Human perception and performance*, *14*, 646-60.

Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nat Neurosci*, *4*, 213-216. doi: 10.1038/84054

Watamaniuk, S. N., & Duchon, A. (1992). The human visual system averages speed information. *Vision research*, *32*, 931-41.

Watamaniuk, S. N., & Sekuler, R. (1992). Temporal and spatial integration in dynamic random-dot stimuli. *Vision research*, *32*, 2341-7.

Watamaniuk, S. N., Sekuler, R., & Williams, D. W. (1989). Direction perception in complex dynamic displays: The integration of direction information. *Vision Research*, *29*, 47-59.

Watson, A. B., & Ahumada, A. J. (1985). Model of human visual-motion sensing. *Journal of the Optical Society of America. A, Optics and image science*, *2*, 322-41.

Weiss, Y., Simoncelli, E. P., & Adelson, E. H. (2002). Motion illusions as optimal percepts. *Nature neuroscience*, *5,* 598-604.

Wertheim, A. H. (1994). Ethics, capital punishment, and pseudoscience. *Perception*, *23*, 1097-100.

Wexler, M., Lamouret, I., & Droulez, J. (2001). The stationarity hypothesis: an allocentric criterion in visual perception. *Vision Research*, *41*, 3023-3037.

Williams, D. W., & Sekuler, R. (1984). Coherent global motion percepts from stochastic local motions. *Vision Research*, *24*, 55-62.

Yuille, A., Grzywacz, N., Processing, M., Watanabe, T., & chapter, E. (1996). *A theoretical framework for visual motion*. Retrieved January 23, 2008, from http://citeseer.ist.psu.edu/yuille96theoretical.html

Zhang, T., Heuer, H. W., & Britten, K. H. (2004). Parietal Area VIP Neuronal Responses to Heading Stimuli Are Encoded in Head-Centered Coordinates. *Neuron*, *42*, 993-1001.