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Perception of time to contact in driving simulators

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Bij de KL bestaat een toenemende behoefte aan advies met betrekking tot de visuele informatie die in een rijsimulator dient te worden aangeboden om de perceptief motorische onderdelen van de rijtaak goed te kunnen vervullen. Met behulp van deze kennis wordt het mogelijk in simulatoren alleen de noodzakelijke beeldinformatie aan te bieden, waardoor het computer gegenereerde beeld (CGI) efficiënt kan worden gebruikt en kosten worden bespaard. In dit kader wordt in opdracht van het COKL het project 'Visuele informatie in voertuigsimulatoren' uitgevoerd.
Bij het besturen van een voertuig is het voor een bestuurder van cruciaal belang dat hij zijn handelingen goed kan timen. Het schatten wanneer een object zal worden bereikt (de tijd tot contact of TTC) is fundamenteel voor een groot aantal aspecten van de rijtaak. Hierbij is visuele informatie van groot belang. In de huidige studie is onderzocht hoe deze informatie het beste in het computer-gegenereerde beeld (CGI) van een rijsimulator kan worden weergegeven.
In de inleiding worden de twee belangrijkste theoretische benaderingen voor de perceptie van TTC, d.w.z. de *directe* en de *inferentiële* benadering besproken. Daarna wordt onderzocht hoe deze informatie het beste in het CGI kan worden weergegeven. In een eerder experiment (Schiff & Detwiler, 1979) waarin een *stilstaande* waarnemer de TTC van een object moest schatten, werd geen effect gevonden van de hoeveelheid visuele informatie (beeldinhoud of -complexiteit) op de TTC schattingen. In het onderhavige experiment is dit experiment uitgebreid met *bewegende* waarnemers die de TTC van stilstaande en bewegende objecten schatten.
De resultaten laten zien dat stilstaande waarnemers niet realistischer schatten in complexe omgevingen, maar bewegende waarnemers wel. Hieruit kan worden opgemaakt dat TTC schattingen vooral gebaseerd zijn op optic-flow informatie. Echter, statische afstandscues kunnen, door redeneren, een bias in de schatting als gevolg van de grootte van het object verminderen. De resultaten laten zien dat directe en inferentiële cues worden gecombineerd bij het TTC schatten.
Om in een rijsimulator een goede TTC perceptie te waarborgen moet in het CGI optic flow van goede kwaliteit worden aangeboden. De resultaten laten zien dat TTC het beste wordt geschat in een complexe omgeving, waarin de waarnemer zijn zelfbeweging goed kan waarnemen. Een voorbeeld hiervan is een scene met op het wegdek een onderbroken middenstreep en duidelijke textuur, en bermpaaltjes en lantaarnpalen langs de weg. Daarnaast dienen afstands- en snelheidscues correct in het beeld te worden weergegeven. Dit betekent dat de gesimuleerde ooghoogte gelijk moet zijn aan de ooghoogte van de bestuurder in de mock-up, en dat de voorwerpen in de database hun echte, prototypische, grootte dienen te hebben (zie ook Korteling & Van Randwijk, rapport IZF 1991 A-11). Doordat de resolutie van het display lager is dan die van het menselijke oog kan de TTC van objecten die een kleine visuele hoek opspannen (objecten die klein en/of ver weg zijn) niet goed worden waargenomen. Bij het modelleren van bepaalde rijoefeningen, zoals het inhalen van een voorligger, dient men er dan ook rekening mee te houden dat bestuurders de TTC van een tegenligger alleen correct kunnen waarnemen als de naderingssnelheid relatief laag is.

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Perception of time to contact in driving simulators

B. Kappé and J.E. Korteling

SUMMARY

When driving a car it is of vital importance that the driver is able to time his actions accurately. Estimating when objects will be reached (the time to contact or TTC) is fundamental to many driving tasks. Visual information is the drivers primary source of TTC information.

The present study investigated the way this information should be modeled in the CGI of a driving simulator, in order to get a realistic performance. In the introduction the two major theoretical approaches, i.e., the *direct* and the *inferential* method of TTC perception are analysed. In a previous experiment (Schiff & Detwiler, 1979), in which *stationary* observers estimated the TTC of approaching objects, no effect of the amount of visual information in the scene (image content or complexity) was found on the estimated TTC. The current experiment extends this previous experiment with *moving* observers estimating the TTC of stationary and moving objects.

Results show that TTC estimates in combination with *stationary* observers are independent of the complexity of the CGI, but that *moving* observers do estimate TTC more realistic with increasing scene complexity. From these results it can be deducted that, when estimating TTC, observers use mainly the information in optic flow.

However, ‘static’ depth cues can, by inference, reduce a bias in the estimates due to differences in the angular size of the approaching object. The conclusion is that direct and inferential cues are integrated when estimating TTC.

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TNO Technische Menskunde
Soesterberg

Het waarnemen van tijd tot contact in rijsimulatoren

B. Kappé en J.E. Korteling

SAMENVATTING

Bij het besturen van een voertuig is het voor een bestuurder van cruciaal belang dat hij zijn handelingen goed kan timen. Het schatten van het tijdstip waarop een object zal worden bereikt (de tijd tot contact of TTC) is fundamenteel voor een aantal aspecten van de rijtaak, bijvoorbeeld bij remmen. Hierbij is visuele informatie van groot belang. In de huidige studie is onderzocht hoe de informatie over de TTC van een voorwerp het beste in het computergegenereerde beeld (CGI) van een rijsimulator kan worden weergegeven. In de inleiding worden de twee belangrijkste theoretische benaderingen voor de perceptie van TTC, d.w.z. *direct* en *door redeneren,* besproken. In een eerder experiment (Schiff & Detwiler, 1979) waarin een *stilstaande* waarnemer de TTC van een naderend voorwerp moest schatten, werd geen effect gevonden van de hoeveelheid visuele informatie in de gegenereerde scènes (beeldinhoud of -complexiteit) op de geschatte TTC. In de huidige studie is dat experiment uitgebreid en schatten *bewegende* waarnemers de TTC van stilstaande en bewegende objecten. De resultaten laten zien dat stilstaande waarnemers niet realistischer schatten in complexe omgevingen, maar bewegende waarnemers wel. Hieruit kan worden opgemaakt dat TTC schattingen vooral gebaseerd zijn op optic-flow informatie. Echter, statische afstandscues kunnen, door redeneren, een bias in de schatting als gevolg van de grootte van het object verminderen. De resultaten laten zien dat beide vormen van TTC perceptie, direct en door redeneren, worden gebruikt bij het schatten van TTC.

1 INTRODUCTION

The use of simulators for driver training and traffic research has become increasingly popular since the introduction of Computer Generated Images (CGI). The visual environment generated by the CGI can be modeled to the desires of the designer, and special effects, such as darkness and fog, can be generated in an instant. In the ideal simulator the driver's response is identical to his 'real world' behaviour under comparable conditions. Due to the physical and technical limitations of the system, this ideal situation is not yet met. For a driving simulator the financial aspect is the major bottle-neck, since driving a car or truck is relatively cheap compared to the cost of a state-of-the-art driving simulator. Since the CGI system is one of the most expensive components of a driving simulator, detailed knowledge on the visual information that is required for a realistic performance can save money. In this report we will investigate how an important aspect of the driver's behaviour, the perception of objects that are on a collision course, should be modeled in a CGI in order to get a realistic performance. The driver's behaviour with respect to the colliding object is based on the time to contact (TTC), for instance in braking (Lee, 1976; Van der Horst & Brown, 1989). The first part of this report deals with the perception of time to contact, and how this variable can be perceived with the CGI. Two ways of time to contact perception are discussed and some ideas concerning the detection of time to contact by the visual system are presented.

In a previous study (Schiff & Detwiler, 1979) considering stationary observers TTC estimates did not depend on scene complexity. In the current experiment we replicated and extended the previous experiment with moving observers estimating the TTC of stationary and moving objects.

1.1 Time to contact

When driving a car, it is crucial that the driver is able to time his actions accurately. Estimating when objects will be reached is fundamental to many driving tasks, for instance in braking (Lee, 1976; Van der Horst & Brown, 1989) and deciding when to make a left turn when vehicles approach in the other lane (Ebbesen, Parker & Konečni, 1977). The amount of time a driver has to perform such a manoeuvre is equal to the Time To Contact (TTC) with the colliding object. TTC is defined as the time it will take, moving at a constant speed, to reach an object, or vice versa (Purdy, 1958, cited in Schiff, 1965). The TTC depends on the relative speed and distance between the object and observer (Eq. 1).

$$\mathrm{TTC} = \frac{\text{Distance}}{\text{Relative Speed}} \qquad \textbf{(1)}$$

Visual information will be the driver's principal source for estimating TTC. The visual information that is available to an observer at a specific point in the environment is called the *optic array* (Gibson, 1950). The optic array can be represented as the perspective projection of the environment on a sphere around the point of observation. All information in the optic array will obey the laws of perspective, for instance, the projected size of an object will be smaller when it is further away. The CGI of a simulator represents the optic array the driver should have seen if he was driving in the modeled environment. Even if the laws of perspective are simulated accurately it is impossible to produce a perfect optic array in a CGI. The resolution of the display is lower than the resolution in the foveal region of the visual field, the image content of the CGI is less rich that a 'real world' optic array, and stereo (disparity and vergence) and accommodation of the lens are not (yet) simulated. The stereo and accommodation cues are considered to be of minor importance for driving a car (Milders & Padmos, 1991).

When the point of observation (e.g. the eye of the driver) is translated relative to the environment, perspective optical transformations are generated. Gibson (1950) called this optic flow or motion perspective. In the flow pattern that is generated by a translation two basic flow components, divergence (DIV) and parallax (SHEAR) can be discriminated (Koenderink, 1986). The DIV component is present in the direction of translation (Fig. 1 a). The vectors of this flow pattern are oriented radially and seem to originate from a single point, the *focus of expansion* (Gibson, 1950). The SHEAR component is present in the plane perpendicular to the direction of translation (Fig. 1 b). The motion vectors in this flow pattern are oriented parallel, which is commonly called motion parallax.

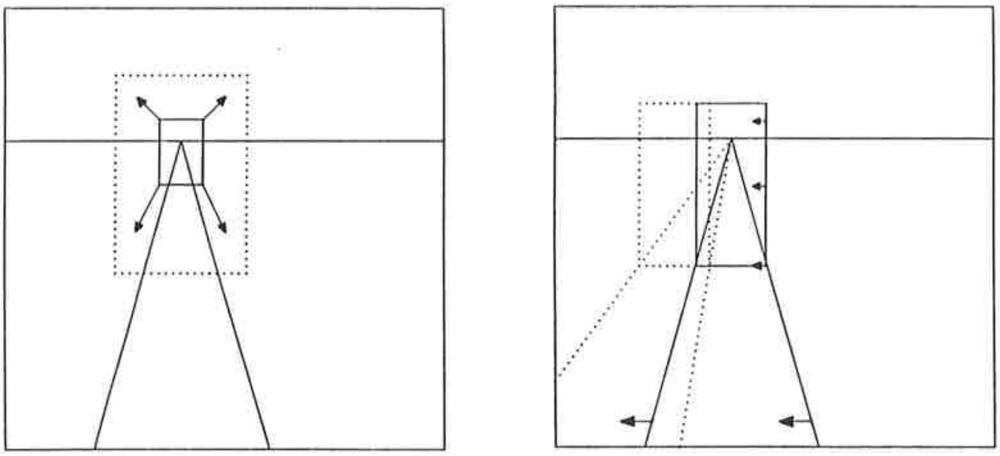

Fig. 1 **a** Optic flow in a DIV flow field; **b** Optic flow in a SHEAR flow field.

The relative size of the vectors in the flow field depends on the distance of the projected object to the point of observation. When moving relative to a static environment a near object will move faster than an object that is further away (Fig. 1 a,b). When the point of observation is translated, the direction of translation dictates the orientation of the flow field in the optic array, and the translational velocity dictates the global speed of all points in the optic array.

Note that the translational flow field can be global, when the observer moves relative to the rigid environment, or local, when an object translates relative to the observer. In both cases the flow can be completely described by the DIV and SHEAR components.

When analysing the perception of TTC, it is important to realize that there is a difference between real world (or distal) variables, such as the size, distance and speed of an object, and the variables of the optic array (proximal or retinal variables), such as the visual angle and angular velocity of the projected image (see Fig. 2). Visual angle (φ) and angular speed

($\dot{\varphi}$) are the only variables that are directly available in the optic array. Size, speed and distance have to be derived from these proximal variables.

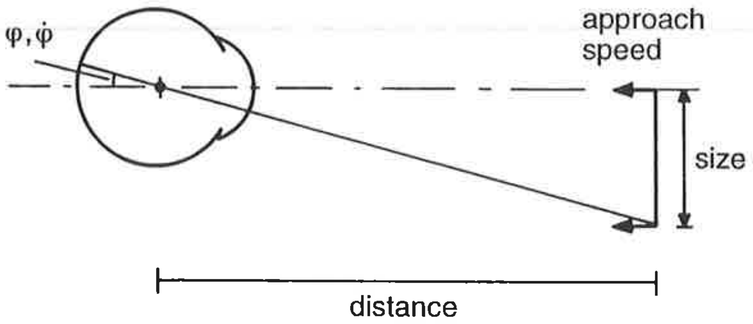

Fig. 2 The visual angle and angular speed depend on the size, distance and approach speed of an object.

The visual angle of the projected image depends on the object's size and the distance between object and observer (Fig. 2, Eq. 2). For small visual angles ($\varphi < 10°$) this can be simplified to Eq. 3. When the distance to the object changes the visual angle will change with a certain angular speed. When the object approaches the observer with a certain speed the derivative of Eq. 2 will give the angular speed at which the image of the object expands (Eq. 4). The expansion speed of an object depends on its size, distance and the approach speed. For objects with a small visual angle ($\varphi < 10°$) Eq. 4 can be simplified to Eq. 5.

$$\varphi = \operatorname{atan}\left(\frac{\text{Size}}{\text{Distance}}\right) \tag{2}$$

$$\varphi = \frac{\text{Size}}{\text{Distance}} \tag{3}$$

$$\dot{\varphi} = -\frac{\text{Size}*\text{Speed}}{\text{Distance}^2+\text{Size}^2} \tag{4}$$

$$\dot{\varphi} = -\frac{\text{Size}*\text{Speed}}{\text{Distance}^2} \tag{5}$$

In literature two fundamentally different ways of TTC perception have been described. The first method, called the 'inferential' method of TTC perception (Groeger & Brown, 1988; McLeod & Ross, 1983; Tresilian, 1990) uses separate estimates of distance and speed. A percept of TTC is obtained by dividing the estimated distance by the estimated speed. The second or 'direct' method of TTC perception does not use separate estimates of distance and speed.

With respect to the 'inferential' method of TTC perception the CGI of the driving simulator should contain information on the distance and approach speed of the object. There are cues that enable **static observers** to estimate the speed and distance of an approaching object. There are three major distance cues. The first distance cue can be used for objects of *known size*. When the absolute size of the object is known, the visual angle spanned by the object in the optic array is inversely proportional to its distance (Eq. 2, 3). The second distance cue is the *ground intercept*. If the observer's eyeheight is known, the visual angle between the bottom of a ground based object and the horizon is inversely proportional to the distance of the object (Eq. 2, 3 Size replaced by Eyeheight). The third distance cue is the *horizon ratio*, the ratio of the part of the object that is visible above and below the horizon gives the size of the object in units of eyeheight. When the size of the object is known it can be used to estimate distance.

When the object is moving towards the stationary observer, local optic flow is generated. There are two speed cues in local optic flow. The first cue can only be used when the object's size and distance are known. The *expansion speed* of the object can be used to estimate approach speed (Eq. 4, 5). A second speed cue can be used when eyeheight is known. The ground intercept provides a distance cue for ground based objects, and the angular speed of the ground intercept is proportional to the approach speed (Eq. 4, 5, replace Size by Eyeheight).

It seems unlikely that **moving observers** do not use 'static' cues for estimating distance and speed. Familiar size, ground intercept, horizon ratio and local expansion speed seem to be equally available to static and moving observers. However, moving observers also have distance and speed cues generated by global optic flow.

There are two distance cues generated by global optic flow. When moving through a static environment the approach speed of all static objects in the scene is equal to the momentary speed of the observer. If the size of the approaching objects is known the expansion speed is inversely proportional to the squared distance, scaled by the speed of the observer relative to the environment (Eq. 4, 5). If the eyeheight is known the angular speed of the ground intercept is also inversely proportional to the squared distance, scaled by the speed of the observer relative to the environment (Eq. 4, 5).

Global optic flow will also generate global speed cues. When moving towards a stationary object the approach speed is equal to the speed of the observer relative to the environment. When the object moves relative to the environment the global optic flow cannot be used to estimate the approach speed of the object unless the motion of the object relative to the environment is known.

Note that all cues on the speed and distance of an object require some a priori knowledge, i.e. the recognition of the object's size, knowing that it is ground based, stationary, or knowing one's eyeheight. Since we live in a visual environment that we know, and in general seem to know our eyeheight, the distance and speed of an object can be estimated. We therefore conclude that the inferential method can and probably will be used in the perception of TTC.

The second or 'direct' method of TTC perception does not use separate estimates of distance and speed. Lee (1976) showed that an optical variable named tau (τ) was equal to the TTC of an approaching object. τ is the *visual angle* of an object divided by the *angular speed* at which it expands (Eq. 6).

$$\tau = \frac{\varphi_t}{\dot{\varphi}_t} \qquad (6)$$

τ is an invariant property of optic flow. This means that it is relatively independent of the content of the optic array; it originates from the laws of perspective that govern the projection of the environment on the retina. When an object moves towards a stationary observer it will generate local optic flow, and thus local τ information. If the observer moves relative to the environment global optic flow is generated, and not only the approached object but also its surround will carry global τ information.

It is to be expected that the properties of the optic array and the way the visual system analyses the visual information are closely linked. During the evolution, and during the post-natal development, the visual system might have been able to tune itself to the basic perspective properties or invariants of the optic array (e.g. Gibson, 1966; Mohn & Van Hoff, 1991; Dodwell, 1991). When applied to the perception of TTC, this means that there might be special purpose neuronal circuits, or smart mechanisms (Runeson, 1977; Van de Grind, 1988) that are able to pick up τ information in the optic flow. In the Appendix we will show that the visual system is indeed able to detect the τ of a stimulus direct, without first calculating the distance and speed of an approaching object.

At this point, we will focus on the perception of another time related measure related to visual perception. This is not relevant for the current experiment, but serves as an extension of the domain. Lee (1976, 1980a) originally developed the τ concept for the DIV component of the optic flow. Later he called the reciprocal of the relative rate of increase over time of *any* variable the *τ-function* of that variable (Lee, 1992). For instance, there is a auditory τ function of the volume of the noise of an approaching vehicle. The volume/increase ratio is equal to the TTC of the approaching object (Schiff & Oldak, 1990). With respect to the visual perception of approaching objects Tresilian (1991, 1993) has shown that the error in TTC estimation based on τ (from the DIV field) alone is larger than the error found when catching a ball some distance lateral to the eye. This implies that other visual sources of information are utilized. The τ function could also be used in the timing of visual events for the SHEAR component of the flow field. This is an appealing idea because SHEAR and DIV are the basic components of the translatory flow field (Koenderink, 1986). When a τ function can be used for both basic components it might be possible to use τ all over the translatory flow field. There are a few indications of the use of a SHEAR flow field in timing tasks.

When driving on a road, the continuous edge lines only show the SHEAR component of the flow field (Kappé & Korteling, 1995). In order to describe the driver's lateral speed control strategy Godthelp, Milgram and Blaauw (1984) developed the time to line crossing (TLC) concept. The TLC is the time it will take before an observer, moving at a constant speed, will cross the road's edge line. The TLC can be defined visually as the τ function of the optical angle between the nearest visible part of the delineation line and a point on the hood of the car[1], and the decrease of this angle. The use of a τ function in a SHEAR flow field

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[1] On a straight road TLC can also be defined as the angle of the edge line relative to a vertical line between observer and the point where the road and horizon meet, divided by the decrease of this angle.

has also been reported by Tresilian (1991, 1993) who only mentions its use in the timing of actions in video games (e.g. the early games of computer tennis with a 'ball' and a 'bat'). Bootsma and Oudejans (1993), and Regan and Kaushal (1993) use a τ function for motion parallel to the observer, but only use it for timing of approaching balls, and do not mention its use in timing of events for the SHEAR component of the flow field. Similar to the detection of τ in a DIV field, it is supposed that special purpose neuronal circuits have evolved that are able to perceive the timing information in a SHEAR flow field.

A major advantage of using τ is that it does not require any *scaling* to 'real world' distal variables, because it is derived from the properties (or 'invariants') of the projection of the environment on the retina. The τ concept is often used as an example of 'direct perception' (Michaels & Carello, 1981; Turvey & Kugler, 1984) since it is an 'invariant' of the optic array and can be picked up by the visual system without further processing. We will consider 'direct perception' as perception through smart neuronal mechanisms that are tuned to specific higher-order properties (or invariants) of the optic array.

The existence of a mechanism for the direct perception of τ is supported by several experiments. Carel (1961) reported a study in which subjects made successful TTC estimates of approaching textured surfaces that filled the entire display, and thus had no distance and speed cues at all. Several authors used short presentation times (300−500 ms) in their experiments on the perception of TTC and have argued that the ability to perceive TTC under these conditions points to fast or direct perceptual mechanisms. In an experiment of Regan and Hamstra (1993) the relevant components in TTC estimation (angular size, expansion speed and τ) were dissociated, showing that the discrimination thresholds for τ were 95 times lower than the thresholds for rate of expansion, with the same stimulus. They also found that the thresholds for τ discrimination were about 5 times lower than the angular size discrimination thresholds. If the cognitive TTC estimation method was used it is expected that the thresholds for angular size and rate of expansion are at least as low as the threshold for τ discrimination.
However, the existence of a direct perceptual mechanism for the perception of τ does not mean that a percept of TTC is based on τ alone. According to Heuer (1993) it seems a fundamental principle of (space) perception that multiple sources of information are integrated to create a percept. He states that there will be other types of information, like disparity, convergence and accommodation of the lens that can be used when perceiving the TTC of an approaching object. We can add memory and experience as well, e.g. knowledge on the size and speed of an object. Also Korteling (1994) points out that a variety of experimental results from neurobiological and psychological research force one to conclude that the nervous system is aimed at the integrative processing of information from multiple sources. An example of the integration of information from other perceptual (sub-)modalities is the combination of visual an auditory information when estimating TTC. Schiff and Oldak (1990) have shown that the auditory analogue of τ can be used to make TTC estimates, and found that TTC estimates were more accurate when optical and auditory stimuli were combined. Another example on the integration of information when estimating TTC is given by the results of Groeger and Brown (1988) who investigated TTC estimation for car drivers and found that the estimates were biased towards inappropriate vehicle noise. Heuer (1993) investigated the use of τ functions of changing size, changing disparity and eye vergence,

and found that all these cues were able to generate a percept of TTC, which was strongest when the cues were combined.

We conclude that even when there is evidence for the direct perception of TTC based upon the τ information in an expanding flow field, other sources of information, such as the use of information from other perceptual (sub-)modalities and 'inferential' distance and speed cues, may be involved in the generation of a percept of TTC. The way the different types of information are integrated, and which stimulus aspect will dominate the percept, may depend on the information content of the stimulus situation that is used, and the task that has to be performed.

1.2 TTC in driving simulators

The driver's visual perception of TTC may be affected by two major shortcomings in CGI systems. First, the complexity of the displayed scenes is limited. Every element that is visible in the CGI has to be calculated by the image generator, and therefore scene complexity is limited by its capacity. For the designer of a visual environment for driving simulation it is important to know which kind of information should be simulated in order to ensure a realistic perception of TTC. If the designer uses the appropriate cues, TTC perception will be optimal with the minimum amount of information. This implies that the image processor is used efficient, and that there is more capacity available for other tasks.
The second shortcoming in the CGI is its limited resolution. The resolution of the display is much lower that the foveal resolution of the human eye. Since the angular size and expansion speed of distant objects with high TTC is quite low it is expected that a low resolution will degrade the TTC perception of such objects even more. This study will address the first problem, i.e., an investigation into the effect of scene complexity on TTC estimation.

Schiff and Detwiler (1979) conducted an experiment on TTC estimation in which they manipulated the complexity of the available visual information. In this experiment the subjects looked at films that were prepared with animated table-top photography. The films showed an approaching square object in several different scenes. The object was stationary for 2 seconds, followed by 2 seconds of approach, thereafter the scene was occluded. The subject's task was to estimate, by pressing a response button, the moment the approaching object would have reached them. The dependent variable was the estimated TTC of the object. The independent variables were scene complexity, TTC at the moment of occlusion, size of the approaching object and distance at the moment of occlusion. Scene complexity was varied in four levels, *(i)* a white plane with horizon and a white sky, *(ii)* an inked rectangular grid terrain with white sky, *(iii)* a grid terrain with grid sky or *(iv)* a white plane with a grid sky. TTC was varied in 5 levels ranging from 2 to 10 s. The dimensions of the approaching object were 3×3 cm or 12×12 cm. The distance of the approaching object at the moment of occlusion was 100 or 200 cm.
The results showed that TTC had a significant main effect. Estimated TTC increased with increasing TTC at the moment of occlusion. The ratio of estimated TTC over TTC was about 0.74. Object size, the distance to the object at the moment of occlusion and scene complexity showed no significant effect on estimated TTC. The authors interpreted this

result as evidence for the use of τ when estimating TTC; object size, distance and scene content do not affect the τ value of the approaching object and therefore should not affect the estimated TTC of the approaching object.

For the designer of visual environments in driving simulators the absence of an effect of scene complexity is promising, since it does not seem to matter how much information is displayed in the scene. However, the scenes with a grid did provide more information on the size and distance of the approaching object, but not on its approach speed carried by optic flow. The stationary observer only has the local optic flow generated by the object itself, the static surround does not generate any optic flow. It can easily be shown that the combination of distance and speed information is essential for TTC perception (Eq. 1), whether direct of inferential. Thus, the lack of an effect of scene complexity might be due to the fact that the scenes were static, and did not generate any optic flow.

In order to gain more insight in the effect of optic flow on TTC perception we replicated the experiment of Schiff and Detwiler (1979) for moving observers. In a driving simulator the subjects estimated the TTC of approaching objects in computer generated scenes with three levels of scene complexity. Motion condition was manipulated in three levels:
- an object moving towards a stationary observer;
- an observer moving towards a stationary object;
- an observer moving towards a moving object.

Again, the subjects briefly saw an approaching square object, in this case for 3 s, and had to press a button the moment they thought the approaching object would have hit their head. The subjects were seated in a mock-up of a car, and the scenes were generated for the correct eyeheight. This ensured that ground intercept and horizon ratio were correctly displayed and perceived in the scenes.
The three scenes varied in the amount of static depth cues and, for moving observers, the amount of optic flow that was generated.
The first scene (Fig. 3 a), called "empty" scene, contained no environmental visual cues at all. In this scene there was no horizon, and, as the size of the object was unknown, no static depth cues were present. In this scene τ was the only cue available.
The second scene (Fig. 3 b), called "primitive" scene, contained a horizon, a road with edge lines, and texture on the road and the surrounding surface. In this scene ground intercept could be used as distance cue and the horizon ratio could give a cue on the object's size. The texture provided information concerning the speed of moving observers and, by occlusion or disocclusion of texture elements, information on the direction and speed at which the object moved relative to the environment.
The third scene (Fig. 3 c), called "complex" scene, was equal to the primitive scene but had a discontinuous centre line and streetlights added to the scene. In the complex scene the size of the object could be compared to the known size of the streetlights. The discontinuous centre line and the streetlights also provided additional optic flow information on the speed of moving observers and moving objects.
The dimensions of the elements in the simple and complex scene, such as road, edge and centre lines, and streetlights, were modeled according to their prototypical size on normal Dutch roads, and could aid the observers to estimate the size of the object more accurately. The method section describes the exact dimensions of the objects in the three scenes.

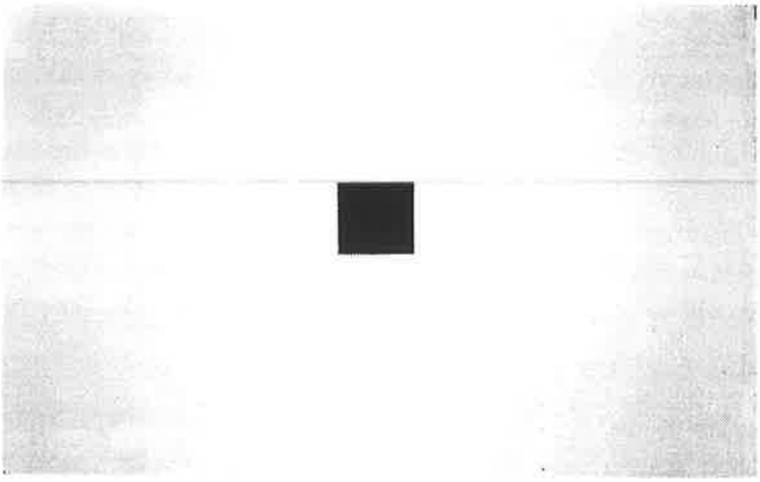

Figure 3 a

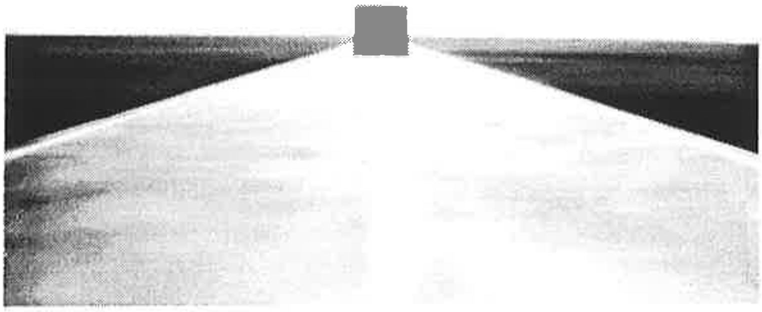

Figure 3 b

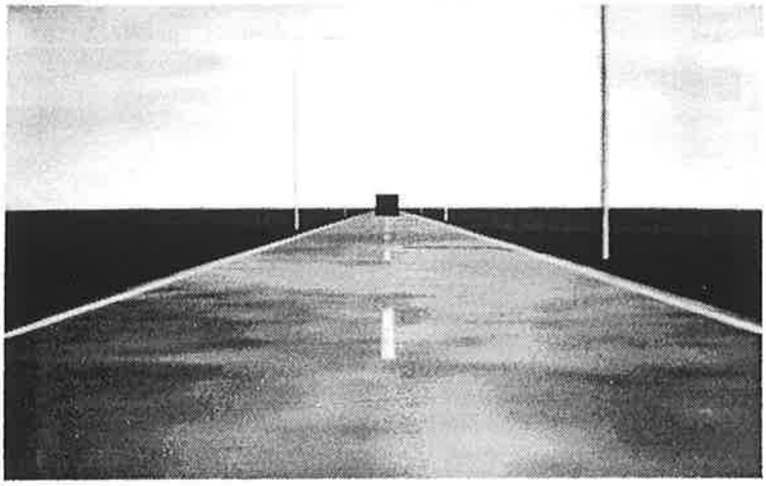

Figure 3 c

Fig. 3 **a** the object in an empty scene; **b** a primitive scene; **c** a complex scene.

Which cues were present in the scene depended on the scene content and on the motion of the observer. The amount of static depth cues depends on the complexity of the scene, more complex scenes contain more static depth cues, and we assume that they will be equally available to stationary and moving observers. However, moving observers are also able to use the information in the optic flow when estimating TTC. The amount of optic flow in the scene also increases with scene complexity. In the empty scene only the expanding object generates optic flow. In the simple and complex scene the texture, the discontinuous centre line and the streetlights will also generate optic flow. The amount of optic flow is largest in the complex scene.

In order to be comparable to the experiment of Schiff and Detwiler (1979), the occlusion paradigm was also used in the current experiment. In this method the approaching object is visible for a short period of time (typically 1–6 s) before the scene is occluded at a certain TTC. The ratio of estimated and actual TTC is taken to be an indication of the quality of the estimate. Most authors take the estimate to be optimal when estimated and actual TTC are equal (e.g. Cavallo & Laurent, 1988). In all studies subjects tend to underestimate TTC, typically about 60% to 80% of actual TTC. Even in the study of Cavallo and Laurent (1988), that was conducted in a moving vehicle, with an unrestricted visual field and normal binocular vision, estimated TTC was about 75% (70% for monocular vision) of the actual TTC (when TTC was 3 or 6 s).

In general, it is assumed that the underestimation is due to a kind of safety margin the subject incorporates in his estimates (e.g. Schiff & Oldak, 1990), but it might as well be that the underestimation originates from the time estimation task in itself (Pöppel, 1987). Because the driver's behaviour in a simulator should resemble his 'real world' behaviour, under comparable conditions, as close as possible (i.e. the *functional validity* of the simulator), in the present study—with a full visual field and monocular vision—a relative TTC of 70% is assumed to be optimal.

Another indicator for the quality of TTC estimation is the standard deviation of a number of repeated TTC estimates. It is expected that in scenes with a high information content the subject is more consistent in his estimate, even when he underestimates the actual TTC by a certain percentage. In order to derive such a consistency measure, in the current experiment each condition was repeated 10 times.

TTC estimation in CGI systems

One of the drawbacks in the current experiment is that the resolution CGI of the simulator (see § 2.2) is probably lower that the resolutions of the films[2] used by Schiff and Detwiler (1979). It is expected that resolution will play a role when the angular size or rate of expansion of an object is small relative to the resolution of the system (large TTCs and/or small, fast approaching objects). In the current experiment we tried to circumvent this problem by choosing the minimum angular size and rate of expansion of the object relatively large compared to the resolution of the CGI (minimum size 18 pixels, minimum rate of

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[2] The authors do not mention the spatial resolution of the films they used. In general the spatial resolution of film is higher than the spatial resolution in CGI's.

expansion about 3 pixels/s). It is expected that resolution does not play a role in large visual angles and angular speeds, i.e. for slow approaching objects and short TTCs.

2 METHOD

2.1 Subjects

Three groups of 10 male subjects participated in the experiments. They all held current driving licences and drove more than 7500 km/y. Their age was 19–30 years (mean 23, SD 2.5). All subjects had normal or corrected to normal vision, and were paid for their participation. The three groups were similar in educational level, driving experience and age.

2.2 Apparatus

The experiment was run on a three channel Evans and Sutherland ESIG 2000 image generator, with an update frequency of 60 Hz. The scene was projected onto a dome and created an image of $150° \times 43°$ visual angle. The average viewing distance to the screen was 3 m and the subject's position was in its optical centre. The scenes were projected by three BARCOGRAPHIC 800 projectors with a resolution of 800×600 (h×v) pixels ($0.067° \times 0.071°$ per pixel) and a refresh rate of 60 Hz. The subjects were seated in a primitive mock-up of a car.

2.3 Task

The subjects viewed the scenes with an approaching object for 3 seconds. Thereafter, the scene was replaced by a uniform grey field with approximately the same luminance as the scene. The subjects were requested to press a response button when they thought that the approaching object would have hit their head. After each response there was a fixed response-stimulus interval of 3 s before a new scene was shown. In order to prevent the use of (incorrect) stereo and vergence cues the subjects used an eyepatch and viewed the scene monocularly. The subjects alternated the viewing eye between each block of trails.

2.4 Independent variables

Five independent variables were manipulated:
- **Motion condition**: object motion | observer motion | both
- **Scene**: empty | primitive | complex
- **Object size**: 3×3 | 4.2×4.2 m
- **Relative speed**: 8.3 | 11.7 | 16.3 m/s
- **TTC**: 2 | 2.8 | 3.92 | 5.49 | 7.68 s (resolution 1/60 s)

Motion condition was between subjects variable, scene, size, speed and TTC were within subject variables. The relative approach speed was similar in all the motion conditions. Table I shows the absolute speeds for object and observer in the three motion conditions.
In order to have the same angular size (φ) and angular speed ($\dot{\varphi}$) values for different stimulus conditions, object size, approach speed and TTC were varied in such a way that visual angle or angular speed were identical for several stimulus conditions (see Table II).

Table I The absolute speeds for the object and the observer for the three relative approach speeds in the three motion conditions.

		Relative speed					
		8.3		11.7		16.3	
		obs.	obj.	obs.	obj.	obs.	obj.
motion condition	observer	8.3	0	11.7	0	16.3	0
	both	11.7	3.3	11.7	0	11.7	-4.6
	object	0	8.3	0	-11.7	0	-16.3

Table II The visual angle (φ in deg) and angular expansion speed ($\dot{\varphi}$ in deg/s) of the object depends on its size, speed and TTCs.

Size 3x3 m

		TTC (s)									
		2.00		2.80		3.92		5.49		7.68	
		φ	$\dot{\varphi}$	φ	$\dot{\varphi}$	φ	$\dot{\varphi}$	φ	$\dot{\varphi}$	φ	$\dot{\varphi}$
speed m/s	8.33	10.29	5.12	7.36	2.62	5.26	1.34	3.76	0.68	2.68	0.35
	11.67	7.36	3.67	5.26	1.88	3.76	0.96	2.68	0.49	1.92	0.25
	16.33	5.26	2.63	3.76	1.34	2.68	0.68	1.92	0.35	1.37	0.18

φ visual angle (deg)
$\dot{\varphi}$ angular speed (deg/s)

Table II (Cont'd)

Size 4.2x4.2 m

		TTC (s)									
		2.00		2.80		3.92		5.49		7.68	
		φ	$\dot{\varphi}$	φ	$\dot{\varphi}$	φ	$\dot{\varphi}$	φ	$\dot{\varphi}$	φ	$\dot{\varphi}$
speed m/s	8.33	14.36	7.11	10.29	3.65	7.36	1.87	5.26	0.96	3.76	0.49
	11.67	10.29	5.12	7.36	2.62	5.26	1.34	3.76	0.68	2.68	0.35
	16.33	7.36	3.67	5.26	1.88	3.76	0.96	2.68	0.49	1.92	0.25

φ visual angle (deg)

$\dot{\varphi}$ angular speed (deg/s)

2.5 Dependent variables

Two dependent variables were registered. The first dependent variable was relative TTC: the ratio between estimated TTC and the actual TTC at the moment of occlusion, expressed as a percentage.
The second dependent variable was the standard deviation of the 10 repeated measures.

2.6 Database

The database of the simulator was programmed to show the three levels of scene complexity. In the empty scene subjects only saw an approaching object on a white screen (Fig. 3 a). In this scene the centre of the object was at eyeheight. The primitive scene contained a horizon, road delineation lines (10 cm wide, 7.20 m apart), and texture on the road and surrounding surface (Fig. 3 b). The complex scene contained a horizon, streetlights (11 m high, 50 m apart, positioned at both sides of the road), continuous edge lines (10 cm wide, 7.20 m apart), a 3−9 intermitted centre line (3 m line, 9 m gap) and texture on the road and on the surrounding surface (Fig. 3 c). In the simple and complex scenes all upright objects were resting on the ground surface and had a small shadow, corresponding with the sun at 160° azimuth and 50° elevation. The dimensions of the elements in the visual scene were according to the standards for normal Dutch roads.
The colliding object was a black square, 3×3 m or 4.2×4.2 m, without texture or fixation mark.

2.7 Procedure

Three groups of 10 subjects were tested, one group for each motion condition. In order to familiarise the subjects with the stimulus they were shown an introductory sequence of 15 trials in which the scenes were not occluded (TTC=15 to TTC=0 s). Then a sequence of 30 randomly chosen trails was practised. During the experiment the subjects were shown a block of trials that consisted of 90 (3 scenes × 3 speeds × 2 sizes × 5 TTCs) trails which took approximately 12 min. Each subject replicated the block 10 times, in which the sequence of 90 trails was randomised for each block. Subjects did not get feedback on their performance. Each day two subjects were tested, who alternated between the experimental blocks.

2.8 Data collection and analysis

The time between the occlusion of the scene and the subjects response (TTC_{est}) was recorded and the relative TTC was calculated ($TTC_{rel} = 100 \times TTC_{est}/TTC$). Due to an error in one of the data-files, only the first nine replications (for all subjects) were analyzed. First a six-factor ANOVA was conducted with motion condition as between-subject variable and five within subject variables; scene, size, speed, TTC and replication. No significant replication effect was found, and the replications were pooled as an error estimate. Since the three empty scenes showed identical information in all motion conditions, this condition could serve as a check for differences between the three groups of subjects. A four factor ANOVA was conducted with motion condition as between subject and size, speed and TTC as within subject variable.

For the pairwise comparison of motion conditions separate ANOVAs were conducted on three pairs of motion conditions. For each motion condition separate ANOVAs were conducted on three pairs of scene conditions.

The standard deviation of TTC_{est} over the nine replications was calculated and analyzed with a five factor ANOVA, with motion condition as between subject variable and scene, size, speed and TTC as between subject variables.

3 RESULTS

The use of the standard deviation of replicated TTC estimates as an indication of the quality of the estimates was found to be uninformative. Apart from an effect of TTC no significant effects were found. A post-hoc correlation analysis showed that the standard deviation of the 9 replications correlated high with TTC_{est}. When TTC_{est} in a certain condition was relatively short, the corresponding standard deviation was smaller. The ratio of SD TTC_{est}/TTC_{est} was only affected by TTC. The standard deviation of the estimates was relatively higher for larger TTCs. The average ratio for the 30 observers was 0.010 and the standard deviation was 0.0019. The ratio was not affected by any of the other independent variables.

The TTC_{rel} results for the empty scenes, in which the stimulus was identical for the three motion conditions (Fig. 4), showed no effect of the experimental conditions, indicating that the three groups of subjects were comparable with respect to the skills required in this experiment, see Fig. 4.

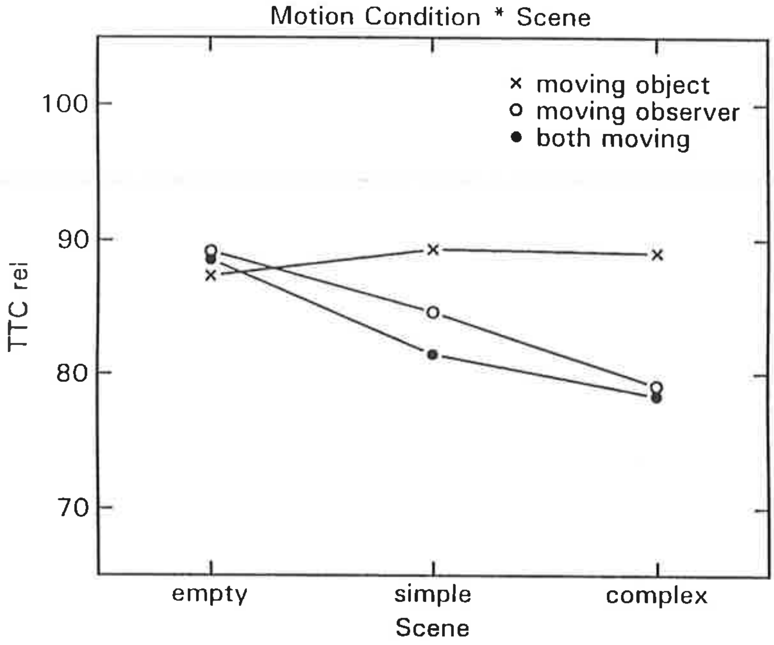


Fig. 4 Relative TTC as a function of scene and motion condition.

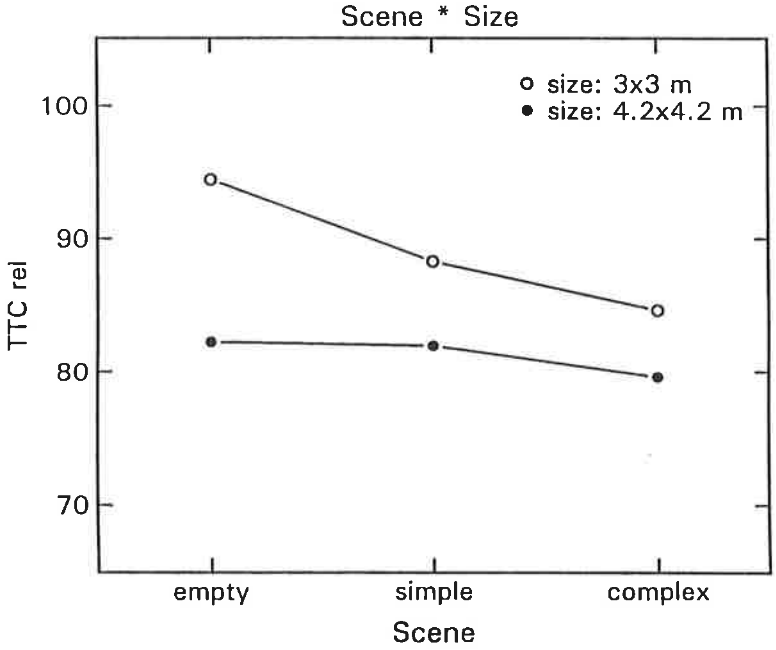


Fig. 5 Relative TTC as a function of scene and object size.

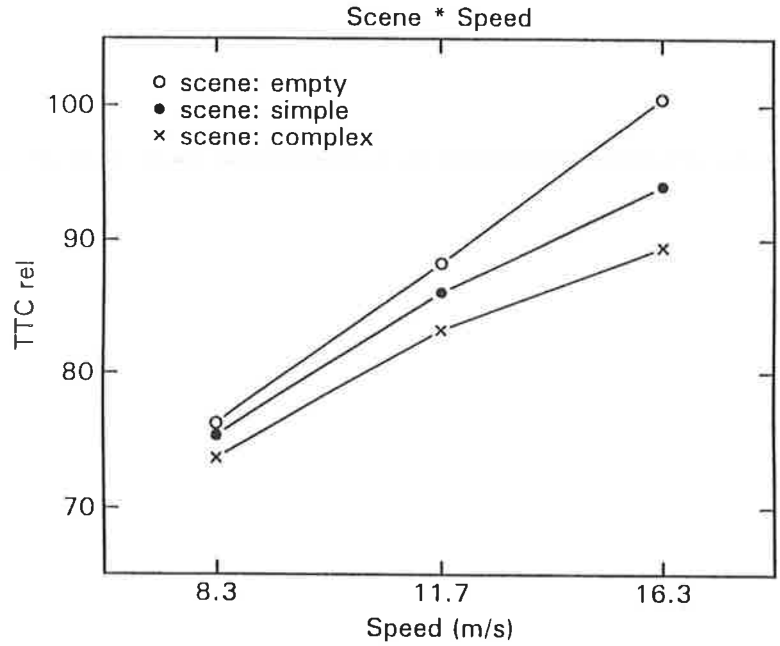
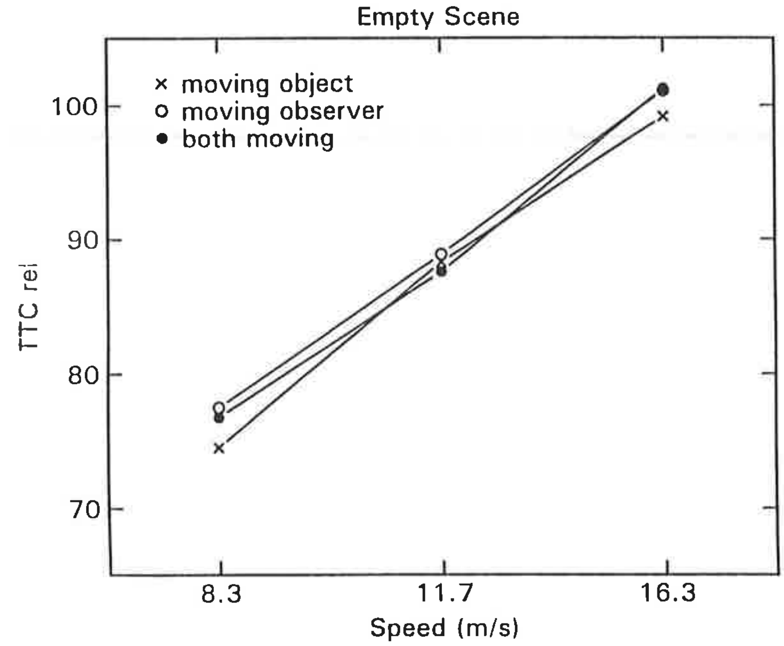


Fig. 6 Relative TTC as a function of scene and speed.

3.1 Effects of motion condition and scene

There were no significant main effects of motion condition on the TTC_{rel} values.
The values of TTC_{rel} decreased [$F(2,54)=13.9$, $p<0.001$] towards the 'realistic' value of 75% when the complexity of the scene increased. An interaction between scene and motion condition [$F(4,54)=6.0$, $p<0.001$] showed that the decrease in TTC_{rel} in complex scenes was strongest when the observer moved and was absent when only the object moved, see Fig. 4.

Figure 5 shows an interaction between scene and object size [$F(2,54)=46.5$, $p<0.001$] which illustrates that the bias to attribute larger objects with lower TTCs is reduced by increasing information in the scenes.
An interaction between scene and speed [$F(4,108)=20.3$, $p<0.001$] showed that the effect of scene increased with increasing speeds, see Fig. 6. A second order interaction of motion condition with scene and speed [$F(8,108)=4.71$, $p<0.001$] shows that the interaction of motion condition and speed is absent in the empty scene, and largest in the complex scene, see Fig. 7.



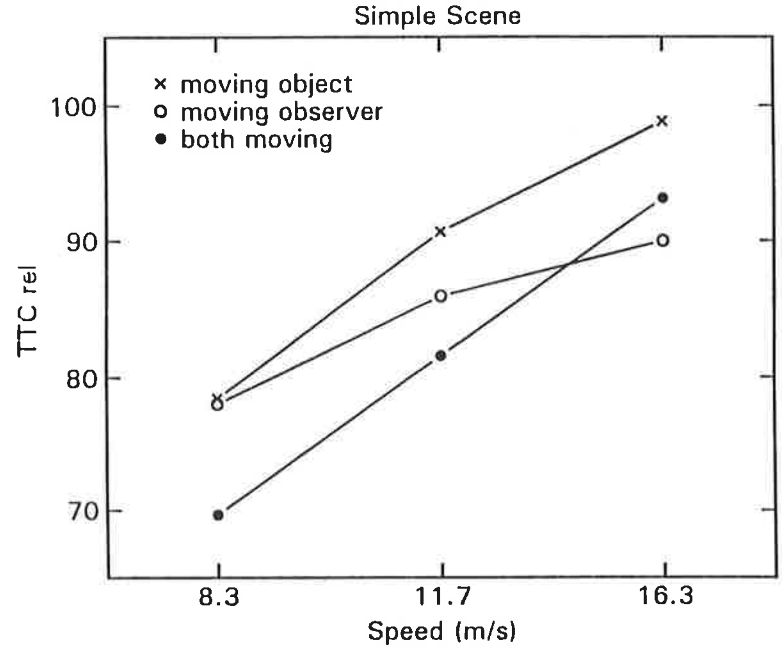
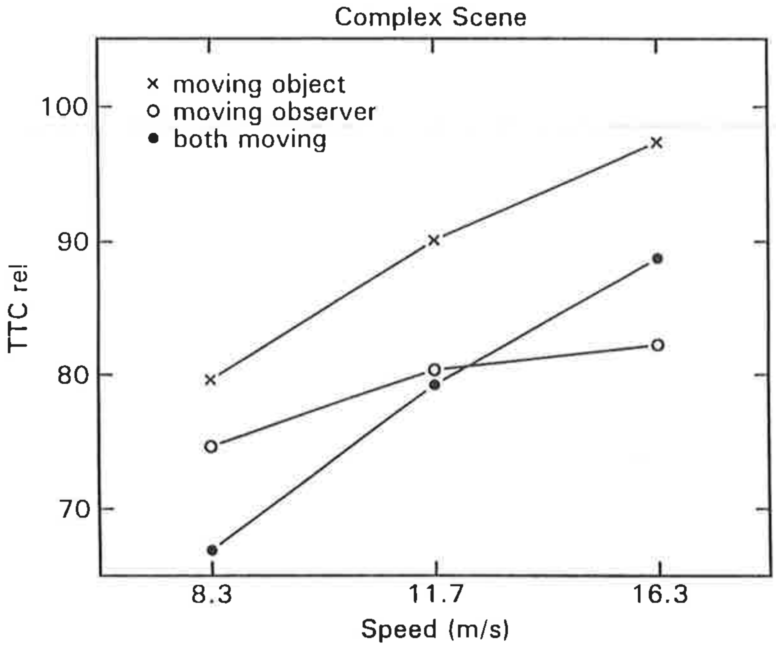


Fig. 7 Relative TTC as a function of motion condition, scene and speed.

Fig. 7 (Cont'd)



3.2 Effects of object size

As shown in Fig. 5, TTC_{rel} was lower [$F(1,27)=220$, $p<0.001$] for the larger object, i.e. subjects tend to estimate the larger object to arrive sooner than the smaller object.

3.3 Effects of speed

The values of TTC_{rel} increased with increasing speeds [$F(2,54)=261$, $p<0.001$], as shown in Fig. 6. Figure 7 shows the interaction of speed with motion condition [$F(4,54)=5.03$, $p<0.005$]; the effect of speed was reduced when the observer moved towards a stationary object.

3.4 Effects of TTC

The main effect of TTC [$F(4,108)=75.2$, $p<0.001$] showed that TTC estimates decrease with increasing TTC values, as shown in Fig. 8. The interactions of TTC with size [$F(4,108)=16.8$, $p<0.001$] show that the increase in estimated TTC due to the effect of size was largest for short TTCs (Fig. 9). The interaction of TTC and speed [$F(8,216)=39.3$, $p<0.001$] shows that the decrease in estimated TTC for slow approaching objects was largest for short TTCs (Fig. 10).

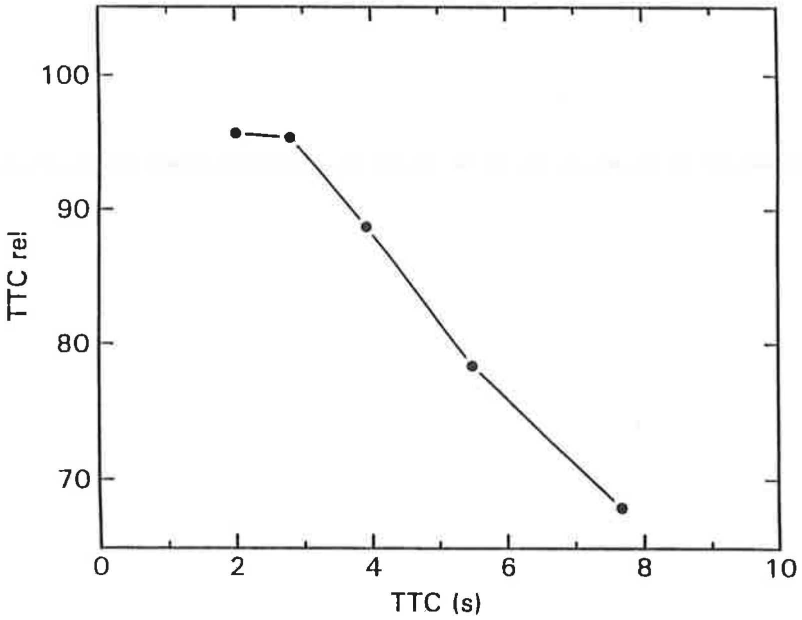


Fig. 8 Relative TTC as a function of TTC.

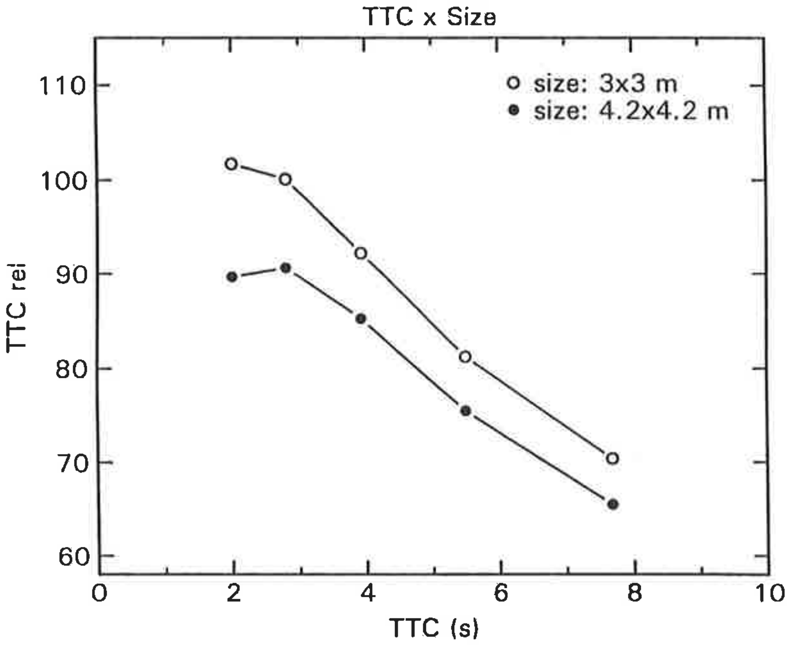


Fig. 9 Relative TTC as a function of TTC and size.

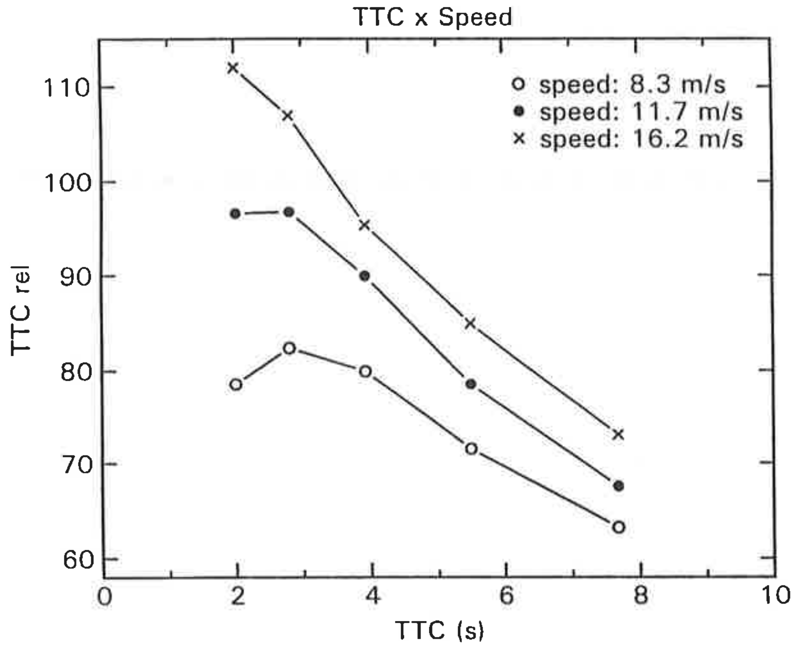


Fig. 10 Relative TTC as a function of TTC and speed.

4 DISCUSSION

Cavallo and Laurent (1988) have found in a field experiment that observers estimate TTC of an object at about 75% of the actual TTC. Since the subjects behaviour in a simulator, performed under comparable conditions, should resemble this real-world behaviour as close as possible we assume an estimate of 75% of the actual TTC to be optimal. The TTC estimates in our experiment are generally about 10% higher, but tend to be lower, and thus more realistic, in the complex scene. It can be conceived that the complex scene contains more direct and inferential cues on TTC, resulting in more realistic estimates.
One of the reasons for the relatively high average estimated TTCs is that an incremental distribution of TTCs was used. In previous experiments (Cavallo & Laurent, 1988; Groeger & Brown, 1988; Heuer, 1993; McLeod & Ross, 1983; Schiff & Detwiler, 1979) it has been found that subjects estimate short TTCs relatively later than long TTCs. Due to the skewed distribution, the short TTCs are relatively overrepresented in the current experiment, resulting in a higher average.

Our data confirm the results of Schiff and Detwiler (1979), who found no effect of scene complexity on the estimated TTC of *stationary* observers (Fig. 4, moving object condition). From these results it can be inferred that static distance cues, such as ground intercept, horizon ratio and relative size, are not used when estimating TTC. The empty scene contains only τ information, and the absence of an effect of more complex scenes suggests that static observers keep on using τ, even when static size and distance cues are available.
However, the present results also show that *moving* observers, approaching stationary or moving objects, *do* make more realistic estimates in simple and complex scenes. This

difference between static and moving observers suggests that global optic flow, generated when moving relative to the environment, is stimulus used in the perception of TTC.
The identical performance in the Moving Observer and Both Moving conditions is remarkable. Since a stationary object is a part of the environment, global optic flow can be used to estimate the TTC of the object more realistic. When the object moves relative to the environment the fixed relation between object and environment is lost, and it seems that the observer only has the local optic flow generated by the object to base his estimate upon. However, this is not what was found. Performance of observers moving towards stationary and moving objects is identical (Fig. 4). Both seem to depend on global optic flow, since are better in complex scenes. This phenomenon can only be explained when we assume that the observer is able to perceive and use the motion of the object relative to the environment.

The results also show that large objects are estimated to arrive earlier than small objects, see Fig. 5. This could be due to a size bias, that is, objects with a larger angular size are perceived to be nearer. An interaction of size and scene (Fig. 5) shows that the bias is smaller in the simple and complex scenes. It thus seems that the static depth cues in the simple and complex scenes, which give an indication of the object's absolute size and distance, reduce the effect of size on the estimated TTCs. Global optic flow does not play a role here, since there was no interaction between size and motion condition.
The main effect of speed shows that the objects approaching at slow speeds are estimated to arrive sooner than the faster approaching objects (Fig. 6). This effect might also be caused by an effect of angular size, as fast approaching objects, for a constant TTC, are further away.

In contrast to the current results, Schiff and Detwiler (1979) did not find an effect of approach speed or object size. An explanation for this effect could be that they used a constant distance at the moment of occlusion (50 or 100 m), and objects with a large difference in size (1.5 m or 6 m). This resulted in an object that could have one of four visual angles at the moment of occlusion, which could be distinguished clearly. In the current study the visual angle of objects was the same for different combinations of size, approach speed and TTC. It is expected that the (subtle) effects of size will be more pronounced in such a situation.

The increase in estimated TTC due to higher approach speeds (Fig. 6) is almost absent for observers moving towards stationary objects (Fig. 7 b,c). The second order interaction of scene, speed and motion condition shows that this reduced effect of approach speed depends on the amount of global optic flow. The reduction is maximal in complex scenes, smaller in simple scenes and absent in empty scenes (Fig. 7 a,b,c). As stated before the effect of speed may be an effect of angular size, because far away objects are smaller, and thus estimated to arrive later. When an observer approached a stationary object, he could move at one of three approach speeds. The observer's impression of the approach speed may compensate the effect of angular size. When approaching slowly the observer's estimates will tend to increase, and when moving fast the observers estimates may tend to decrease (Fig. 7 b,c).

The estimated TTCs are relatively high for short TTCs (Fig. 8), and decrease with increasing TTC. This trend has been found in many experiments that involve the occlusion method for time to contact estimation (Schiff & Detwiler, 1979; Cavallo & Laurent, 1988; McLeod & Ross, 1983). In Fig. 11 the results of these experiments are combined with the results of the current experiment (estimated TTCs).

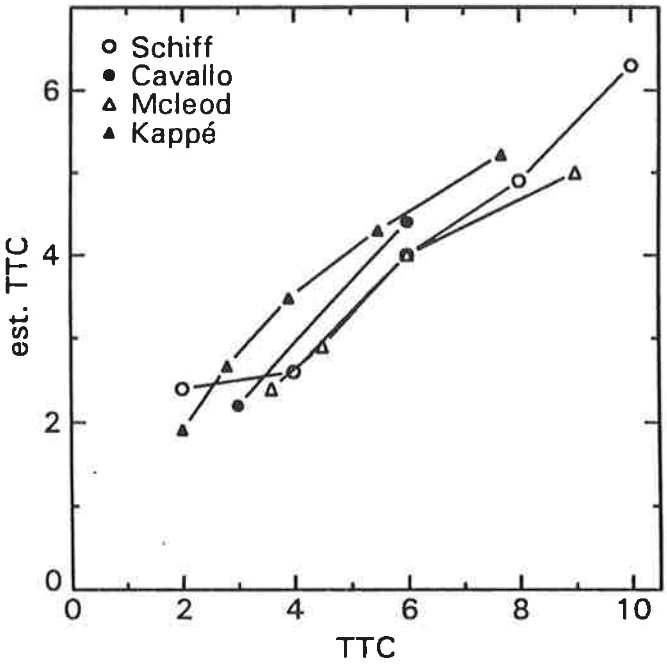


Fig. 11 Estimated TTC as a function of TTC in the current and in previous experiments.

On average our results are slightly higher, but are within the range spanned by the other experiments. A range effect, the observer's tendency to estimate a value towards the centre of the range spanned by the variable, might be the reason for the relatively high estimates at low TTCs and lower estimates for the long TTCs. Also the effect of the time estimation task in itself could play a role here, because subjects are known to overestimate the length of a temporal interval shorter than 2–3 seconds and tend to underestimate its length when the interval is longer than 2–3 s (Pöppel, 1978, 1987). However, the experiments of Pöppel were done with entirely different tasks, and it is uncertain whether these results may be applied to TTC estimation tasks.

An interaction between TTC and size (Fig. 9) showed that the effect of size was largest for short TTCs. The difference in visual angle between the small and the large object will be largest for near objects (short TTCs). This suggests that the subjects bias due to the angular size of the object will be largest in these conditions. Also an interaction of TTC and speed (Fig. 10) showed that the effect of speed was largest for short TTCs. As mentioned before it can be inferred that the effect of speed is an effect of angular size. The differences in angular size due to speed will be largest for short TTCs.

5 CONCLUSIONS

The results of the experiment show that optic flow is the main source of information when estimating the TTC of an approaching object. When the observer moves, global optic flow is generated, leading to more realistic estimates in simple and complex scenes. The estimates of stationary observers do not improve with increasing scene complexity, which may seem to rule out the use of 'static' or 'inferential' distance cues when estimating TTC.

Since τ is the only information in the empty scene, and the estimates are similar in simple and complex scenes, this seems to indicate that stationary observers based their estimates on the 'direct' τ information only. However, the results also show that 'inferential' cues on absolute size and distance, such as ground intercept and horizon ratio, are used to reduce the bias due to differences in angular size of the approaching object. The differences in angular size are caused by different approach speeds, and by using objects with two different sizes. The conclusion is that subjects use both 'direct' and 'inferential' cues when estimating TTC of an approaching object.

The results show that, in order to ensure correct TTC perception in driving simulators, the CGI should contain high quality optic flow information. The amount of information needed is not known, but the results for the simple environment show that even with sparse flow fields the estimates improve substantially. The CGI should also contain static depth cues like ground intercept and horizon ratio, which means that the simulated eyeheight should be equal to the eyeheight of the observer in the mock-up, and that the size of the simulated objects should be equal to their prototypical real world size, as suggested by Korteling and Van Randwijk (1991).

REFERENCES

Bootsma, R.J. & Oudejans, R.R.D. (1993). Visual information about time-to-collision between two objects. *Journal of Experimental Psychology: Human Perception and Performance*, 19(5), 1041-1052.

Carel, W.L. (1961). *Visual factors in the contact analog.* Publication R61ELC60, Ithaca, NY: General Electric Co. Advanced Electronics Center.

Cavallo, V. & Laurent, M. (1988). Visual information and skill level in time to collision estimation. *Perception*, 17, 623-632.

Dodwell, P.C. (1991). Transformation after Gibson: biological and ecological constraints on vision. In J.R. Cronly-Dillon (Ed.), Vol. 14 (Pattern Recognition by Man and Machine) of *Vision and Visual Dysfunction*.

Ebbesen, E.B., Parker, S. & Konečni, V.J. (1977). Laboratory and field analyses of decisions involving risk. *Journal of Experimental Psychology: Human Perception and Performance*, 3, 576-589.

Gibson, J.J. (1950). *The perception of the visual world.* Boston: Houghton Mifflin.

Gibson, J.J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

Godthelp, J. & Konings, H. (1981). Levels of steering control; some notes on the time-to-line crossing concept as related to driving strategy. In: *Proceedings of the First European Annual Conference on Human Decision and Manual Control* (pp. 343-357). Delft, NL: Technical University.

Godthelp, J., Milgram, P. & Blaauw, G.J. (1984). The development of a time-related measure to describe driving strategy. *Human Factors*, 26(3), 257-268.

Groeger, J.A. & Brown, I.D. (1988). Motion perception is not direct with indirect viewing systems. In A.G. Gale et al. (eds), *Vision in Vehicles II.* Amsterdam: Elsevier Science Publishers B.V. (North-Holland).

Heuer, H. (1993). Estimates of time to contact based on changing size and changing target vergence. *Perception*, 22, 549-563.

Johansson, G. (1975). Visual Motion Perception. *Scientific American*, 232(6), 76-88.

Kappé, B. & Korteling, J.E. (1995). *Visual information in vehicle simulators: lateral control on a straight road.* Report TNO-TM (in Dutch, in prep.), Soesterberg, NL: TNO Human Factors Research Institute.

Koenderink, J.J. (1986). Optic Flow. *Vision Research*, 26(1), 161-180.

Koenderink, J.J. (1990). Some theoretical aspects of optic flow. In R. Warren & A.H. Wertheim (Eds.), *Perception and control of self motion* (pp. 53-68). Hillsdale, NJ: Lawrence Erlbaum Associates.

Koenderink, J.J. & Van Doorn, A.J. (1985). Spatial and temporal parameters of human motion detector properties in the monocular visual field. *Journal of the Optical Society of America*, 2, 252-259.

Korteling, J.E. (1994). *Multiple task performance and aging*. Thesis Rijksuniversiteit Groningen, ISBN 90-9006920-8.

Korteling, J.E. & Van Randwijk, M.J. (1991). *Simulators and training grounds in military driver training; literature survey and advice.* Report IZF 1991 A-11 (in Dutch), Soesterberg, NL: TNO Human Factors Research Institute.

Lee, D.N. (1976). A theory of the visual control of braking based on information about the time to collision. *Perception*, 5, 437-459.

Lee, D.N. (1980). Visuo-motor coordination in space-time. In G.E. Stelmach & J. Requin (Eds.), *Tutorials in motion behaviour* (pp. 281-295). Amsterdam: North-Holland.

McLeod, R.W. & Ross, H.E. (1983). Optic flow and cognitive factors in time-to-collision estimates. *Perception*, 12, 417-423.

Michaels, C.F. & Carello, C. (1981). *Direct perception.* Englewood Cliffs, NJ: Prentice-Hall.

Milders, M.V. & Padmos, P. (1991). *Requirements for outside-world images of vehicle simulators; a literature survey.* Report IZF 1991 B-6 (in Dutch), Soesterberg, NL: TNO Human Factors Research Institute.

Mohn, G. & Van Hoff, J. (1991). Development of the visual system. In J.R. Cronly-Dillon & D. Regan (Eds.), Vol. 10 (Spatial Vision) of *Vision and Visual Dysfunction.*

Nakayama, K. (1985). Biological image motion processing: a review. *Vision Research*, 25(5), 625-660.

Pöppel, E. (1978). Time Perception. In R. Held, H.W. Leibowitz & H.L. Teuber (Eds.), *Handbook of sensory psychology, Vol 8. Perception.* Berlin: Springer-Verlag.

Pöppel, E. (1987). Time Perception. *Encyclopedia of Neuroscience* (pp. 1215-1216). Boston: Birkhäuser.

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

Regan, D. & Hamstra, S.J. (1993). Dissociation of discrimination thresholds for time-to-contact and for rate of angular expansion. *Vision Research*, 33(4), 447-462.

Regan, D. & Kaushal, S. (1993). Monocular discrimination of the direction of motion in depth. *Vision Research*, 34(2), 163-177.

Runeson, S. (1977). On the possibility of 'smart' perceptual mechanisms. *Scandinavian Journal of Psychology*, 18, 172-179.

Schiff, W. (1965). Perception of impending collision: a study of visually directed avoidant behaviour. *Psychological Monographs*, 79, whole number 604.

Schiff, W. & Detwiler, M.L. (1979). Information used in judging impending collision. *Perception*, 8, 647-658.

Schiff, W. & Oldak, R. (1990). Accuracy of judging time to arrival: Effects of modality, trajectory and gender. *Journal of Experimental Psychology: Human Perception and Performance*, 16(2), 303-316.

Tresilian, J.R. (1990). Perceptual information for the timing of interceptive action. *Perception*, 19, 223-239.

Tresilian, J.R. (1991). Empirical and theoretical issues in the perception of time to contact. *Journal of Experimental Psychology: Human Perception and Performance*, 17(3), 865-876.

Tresilian, J.R. (1993). Four questions of time to contact: a critical examination of research on interceptive timing. *Perception*, 2, 653-680.

Turvey, M.T. & Kugler, P.N. (1984). The ecological approach to perceiving and acting. In H.T. Whiting (Ed.), *Human motor actions: Bernstein readressed* (pp. 373-412). Amsterdam: North-Holland.

Van de Grind, W.A. (1988). The possible structure and role of neuronal smart mechanisms in vision. *Cognitive Systems*, 2, 163-180.

Van der Horst, A.R.A. & Brown, G.R. (1989). *Time-To-Collision and driver decision-making in braking.* Report IZF 1989 C-23, Soesterberg, NL: TNO Human Factors Research Institute.

Van Doorn, A.J. & Koenderink, J.J. (1982a). Temporal properties of the visual detectability of moving spatial white noise. *Experimental Brain Research*, 45, 179-188.

Van Doorn, A.J. & Koenderink, J.J. (1982b). Spatial properties of the visual detectability of moving spatial white noise. *Experimental Brain Research*, 45, 189-198.

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APPENDIX The detection of τ

Here we will try to show that there are neuronal circuits in the visual system that are sensitive to τ. If the visual system is able to directly pick-up the τ information from the optic flow, it has to be able to combine visual angle and angular speed. The analogue of visual angle in the optic array is location on the retina, as a stimulus with a certain eccentricity (azimuth and elevation) relative to the viewing direction will always be projected on the same retinal location. Since the retina is packed with receptors, the stimulus will be registered by each neuron that has its receptive field on that location. In general it is believed that angular motion is registered by a smart mechanism that combines the output of two nearby receptors. This 'bilocal correlator' mechanism has been studied extensively (e.g. Van Doorn & Koenderink, 1982a, 1982b, see Nakayama, 1985, for a review). Each correlator is sensitive for motion in one direction and one speed. It is estimated that on each location of the retina there are about 150 bilocal correlators (Koenderink, 1985). The correlators output is a 'labelled line': if the line is active, a stimulus is passing with a certain direction and speed. The crux of the bilocal correlator in the perception of τ is its sensitivity to *angular motion at a specific location* in the visual field; at a specific visual angle a specific angular speed is detected. If one is fixating on the focus of expansion the output of a bilocal correlator signals a specific τ value. In Fig. 2 this principle is explained. On two locations on the retina, both 2° from the fovea, two bilocal correlators are shown. The bilocal correlators are tuned to different speeds, in this case the upper to 0.5 deg/s and the lower to 2 deg/s. If the stimulus activates the upper detector, its TTC is 2/0.5=4 s. If the stimulus activates the lower detector its TTC is 2/2=1 s.

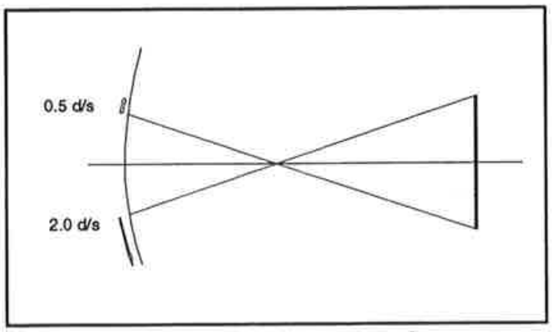

Fig. 12 The detection of τ.

Note that there is no need to fixate on the focus of expansion when the outputs of two or more bilocal correlators are combined. When the stimulus in Fig. 12 stimulates both bilocal correlators at the same time the stimulus has a TTC of (2+2)/(2+0.5)=1.6 s (note that the stimulus must now be moving along the thick line). If the visual system is able to combine the output of multiple bilocal correlators with respect to their relative positions (angular separations) it allows for the detection of τ anywhere in the visual field. The question arises wether the visual system 'knows' which bilocal correlators should be combined. According to Gibson (1966) the visual system is indeed able to recognise the motion patterns in the optic flow. Also Johansson (1975) has shown that observers are able to 'see' a walking man in the dark, only from the motion of lights attached to the man's joints. This result shows that the brain is able to decide which motion belongs to what object. Analogue to the perception of the motion pattern of the walking man also DIV or SHEAR motion patterns (or their combination) might be perceived. If this is true the detection of TTC or TLC is encoded in the combination of the pattern's size and magnitude of the gradient in the motion pattern. Thus TTC or TLC are not calculated in terms of the division of angular size and angular speed, but are recognised as patterns and are a property of the approaching object in the same way that for instance its colour is.

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When driving a car it is of vital importance that the driver is able to time his actions accurately. Estimating when objects will be reached (the time to contact or TTC) is fundamental to many driving tasks. Visual information is the drivers primary source of TTC information.

The present study investigated the way this information should be modeled in the CGI of a driving simulator, in order to get a realistic performance. In the introduction the two major theoretical approaches, i.e., the direct and the inferential method of TTC perception are analysed. In a previous experiment (Schiff & Detwiler, 1979), in which stationary observers estimated the TTC of approaching objects, no effect of the amount of visual information in the scene (image content or complexity) was found on the estimated TTC. The current experiment extends this previous experiment with moving observers estimating the TTC of stationary and moving objects.

Results show that TTC estimates in combination with stationary observers are independent of the complexity of the CGI, but that moving observers do estimate TTC more realistic with increasing scene complexity. From these results it can be deducted that, when estimating TTC, observers use mainly the information in optic flow.

However, 'static' depth cues can, by inference, reduce a bias in the estimates due to differences in the angular size of the approaching object. The conclusion is that direct and inferential cues are integrated when estimating TTC.

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