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Visual information and skill level in time-to-collision estimation

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Abstract. Previous studies on the visual origin of time-to-collision (T_c) information have demonstrated that T_c estimates can be based solely on the processing of target expansion rate (optic variable τ). But in the simulated situations used (film clips), there was little reliable information on speed (owing to reduced peripheral vision) and distance (owing to the absence of binocular distance cues) available. In order to determine whether these kinds of information are also taken into account, it is necessary to take an approach where the subject receives a more complete visual input. Thus, an experiment conducted on a circuit under actual driving conditions is reported. Experienced drivers and beginners, who were passengers in a car, had to indicate the moment they expected a collision with a stationary obstacle to take place. Subjects were blindfolded after a viewing time of 3 s. The conditions for speed evaluation (normal versus restricted visual field) and distance evaluation (binocular versus monocular vision) by subjects were varied. The approach speed (30 and 90 km h^{-1}) and actual T_c (3 and 6 s) were also varied. The results show that accuracy of T_c estimation increased with (i) normal visual field, (ii) binocular vision, (iii) higher speeds, and (iv) driving experience. These findings have been interpreted as indicating that both speed and distance information are taken into account in T_c estimation. They suggest furthermore that these two kinds of information may be used differently depending on the skill level of the subject. The results are discussed in terms of the complementarity of the various potentially usable visual means of obtaining T_c information.

1 Introduction

The concept of time-to-collision—which is also sometimes called time-to-contact or time-to-go, depending on the type of situation under investigation—has attracted considerable attention in recent years in studies on the visual control of locomotion, particularly since Lee proposed his extensive formal models for the timing of action (1974, 1976).

A driver on a collision course with either a stationary obstacle or another moving vehicle must anticipate the moment of the impending collision in order to decide when to start braking and when to make any necessary adjustments during braking. Time-to-collision (T_c), ie the time it will take to reach the obstacle, is a crucial predictor in these regulatory actions. The interesting heuristic possibilities of this concept certainly explain to a great extent why it has been so widely used in a large number of visually guided situations. It was originally devised to deal with behaviours such as the avoidance of oncoming objects by stationary subjects (Ball and Tronick 1971; Bower et al 1970; Carel 1961; Dunkeld and Bower 1980; Purdy 1958; Schiff 1965; Yonas et al 1977). The concept was then extended to situations in which an observer moves relative to a stationary or moving object, as in the case of long jumping (Lee et al 1982), braking (Laurent et al submitted; Lee 1976), and car following (Lee 1976). It has even been applied to trajectory control (Godthelp et al 1984). Current research (including the present study) has focused on the second type of situation, in particular on the question of what kind of visual information T_c is based on. T_c has been defined in these situations as the time taken by an observer travelling at constant speed to reach a specific point on his path.

Three main hypotheses can be formulated as to the nature of the visual information used to obtain T_c. According to the first of these, which is in line with the ecological optics approach (Gibson 1950, 1966, 1979; Lee 1974, 1976), T_c might be based on optic-flow information provided by the expansion of the target-object being approached by the observer. Lee (1976) has demonstrated mathematically how T_c can be specified by the optic variable τ, which is the inverse of the rate of dilation of the target's image on the retina. On the basis of this model, McLeod and Ross (1983) have proposed the following formula:

$$T_c = \frac{\theta_1}{(\theta_2 - \theta_1)/(t_2 - t_1)},$$

where θ_1 and θ_2 are the angular separations between any two target image points on the retina at times t_1 and t_2 respectively. Thus $(\theta_2 - \theta_1)$ represents the apparent target expansion during the observation time $(t_2 - t_1)$. The authors claim that the simplicity and efficiency of this so-called optic-flow method make it a useful tool: it gives T_c without requiring any computational effort, and the moving observer needs only to watch the target in front of him.

There exist also other potentially usable means of obtaining T_c information, involving, in particular, information about the observer's speed and his distance from the target. Vection experiments (Brandt et al 1973; Pavard and Berthoz 1976) as well as studies on speed estimation (Salvatore 1968) have shown that speed information that relies on sensations of self-motion depends on peripheral visual stimulation. In real vehicle-approach situations, on the other hand, a great number of distance cues, such as binocular disparity, texture gradient, and occlusion, are simultaneously available. Only the oculomotor information sources (convergence, accommodation) are of negligible value when longer distances are involved.

A second method of obtaining T_c could be based on vehicle speed and its distance from the obstacle, according to the following formula:

$$T_c = \frac{\text{distance}}{\text{speed}}.$$

This method assumes that both distance and speed are taken into account in T_c estimation, since neither of these parameters on its own provides the subject with sufficient information. In fact, there is little practical benefit to be gained from knowing, for example, the absolute distance from an obstacle; in order to start braking or to take avoiding action, the driver also needs to assess his own speed and to use both parameters to judge when to alter course. For this reason this method is sometimes referred to as a cognitive or computational strategy (Lee and Reddish 1981; McLeod and Ross 1983).

A third way of obtaining T_c, which relies on distance-change information, can be expressed as follows:

$$T_c = \frac{d_1}{(d_1 - d_2)/(t_1 - t_2)},$$

where d_1 and d_2 are the distances between the observer and the obstacle at times t_1 and t_2 respectively. Thus $(d_1 - d_2)$ represents the distance change relative to the obstacle during the observation interval $(t_1 - t_2)$. We would note that the driver does not need here to evaluate the distance in absolute terms, but simply to perceive its change, which represents great savings in the amount of data processing required.

Although earlier studies seem to support the use of a τ-strategy, we would stress that they did not in fact really lend themselves to the testing of alternative hypotheses.

Indeed, until now this question has been analysed in only two types of situation, in neither of which was it possible to separate out the different sources of information involved. First, the use of 'natural' situations (automobile driving, Lee 1976; plummeting gannets, Lee and Reddish 1981; long jumping, Lee et al 1982) implies that all kinds of information are usable, without it being possible to identify the nature of the information actually used. The opposite type of, artificial, situation, however, does not offer favourable conditions for distance and speed assessment (eg the visual 'immobilisation' of the subject on a treadmill, Warren et al 1986; the use of film clips which suppress binocular distance cues and limit visual stimulation to a 15-30 deg field, McLeod and Ross 1983; Schiff and Detwiler 1979). While this type of stimulation allows the τ-strategy process to operate (because it requires only that the subject simply views the obstacle), the other types of process require the subject to receive a more complete visual input that includes reliable information on speed and distance.

In this context, we felt it necessary to take a complementary approach consisting of the manipulation of visual information in a real-life task where all kinds of information were available. For this purpose, we conducted experiments under actual driving conditions when we varied in particular the visual conditions relating to the assessment of speed and distance, in order to establish whether these two parameters are involved in the estimation of T_c. Another question raised in this context and not examined before concerns the possible existence of differences in the need for visual information depending on the skill level of the subject. We can hypothesise that previous driving experience may modify both quantitatively and qualitatively the use of available redundant information and that of subsequent processing strategies in assessing T_c.

2 Method

2.1 *Subjects*

Twenty-four male volunteers, twelve of whom were experienced drivers and twelve beginners, participated in the experiment. Their ages ranged from 18 to 40 years. All had normal vision.

2.2 *Experimental conditions*

We tested the contributions of the following four factors (each involving two possible conditions) to the estimation of T_c:
(i) visual field (normal field versus field restricted to a 10 deg visual angle),
(ii) vision (binocular or monocular),
(iii) actual time-to-collision (3 or 6s),
(iv) speed of the vehicle (30 or 90 km h^{-1}).
The sixteen experimental situations, representing all possible combinations of these four factors, were arranged in a random order. Half of the subjects were tested in this order, and the other half in the opposite order.

It should be mentioned that the actual T_c (3 and 6 s) was chosen to be below the limit of 8-10 s above which accuracy has been found to drop considerably (Schiff and Detwiler 1979; Thomson 1983). The experiment was conducted under conditions of

Table 1. Visual conditions in the various experimental situations.

T_c/s	Speed/km h^{-1}	Final distance from target/m	Final size of target/deg	Final velocity of target/deg s^{-1}
6	90	150	0.30	0.10
6	30	50	0.92	0.31
3	90	75	0.62	0.41
3	30	25	1.83	1.22

good visibility (in dry, clear weather). Thus we can assume that in all our experimental conditions the visual angular velocities of the target were above threshold, which we, like Lee (1976), take to be about 0.08 deg s^{-1}. The visual conditions in the experiment are summarised in table 1. It can be seen that in all cases the target expansion rate was visually available for assessment of T_c.

2.3 *Procedure*

The experimental procedure, which was based on that used by Thomson (1983), was similar to that used in our earlier experiments (Cavallo et al 1988; Laurent and Cavallo 1985). The experiment was conducted on a driving circuit. The subject was a passenger in a car travelling in a straight line at a constant speed towards a visual target. The target, a stationary obstacle, was a mock-up of the rear of a car on the road. At first, while approaching the target, the subject could not see his environment. He was then allowed a viewing time of 3 s, after which his visual field was again obstructed, with the vehicle either 3 or 6 s from the target. The target was removed during the obstruction period. The subject was required to press a button at the moment when he expected the vehicle to collide with the target object. There was no familiarisation period nor any feedback to the subject on the accuracy of his estimates, in order to prevent learning processes from taking place.

2.4 *Apparatus*

The subject was required to wear a helmet with a visor that could be opened and closed by a photoelectric cell fitted to the car. The cell was triggered when the car crossed reference marks made with reflective sheeting placed on the road. Another photoelectric cell was triggered when the target was reached. From a recording of the exact times at which the visor was opened and closed and those at which the vehicle passed the target, together with the responses produced by the subject, it was possible to monitor the various situation parameters, in particular the vehicle's speed, and subsequently to weight the T_c estimated by the subject so as to take the exact speed of the vehicle into account. The visual field was restricted to 10 deg by virtue of the subjects wearing special individually-adapted glasses. So as to estimate any auditory information about speed, the subjects wore headphones which emitted white noise.

3 Results

Figure 1 shows the relationship between the mean estimated T_c and actual T_c for experienced drivers and beginners. The real T_c was systematically underestimated. Figure 1 also shows, as has been shown in earlier studies, that the underestimation of T_c increased as actual T_c increased, while the proportional error magnitude remained almost constant, at between 29 and 28% for the experienced drivers and between 46 and 48% for the beginners.

The estimates can be satisfactorily described by a visually-fitted straight line passing through the origin with a gradient of 0.72 for the experienced drivers and 0.54 for the beginners. Regression calculations yielded the equations $y = 0.73x + 0.04$ for the experienced drivers and $y = 0.57x + 0.15$ for the beginners, which is very similar to those representing the visually fitted lines. The average slope obtained was 0.65, which is comparable to the slope of 0.61 obtained by Schiff and Detwiler (1979) and that of 0.58 obtained by McLeod and Ross (1983).

Given the fact that the results were proportional, we converted the data into percent accuracy scores, so as to eliminate the effect of actual T_c. Since T_c was systematically underestimated, we can state that the higher the T_c estimates, the greater the accuracy.

The percent accuracy scores were subjected to an analysis of variance (ANOVA). Preliminary examinations revealed no order effect, which enabled us to simplify our subsequent analysis. We then undertook a five-factor ANOVA with driving experience as the between-subject variable and the four factors—visual field, vision, actual T_c, and speed—as the within-subject variables. A posteriori comparisons (Scheffé tests) completed the analysis.

The effects of visual field, vision, and vehicle speed are shown in figure 2. It can be seen that the accuracy increased in conditions involving binocular vision (63.8 versus 60.8%; $F_{1,22} = 11.96$, $p < 0.005$), normal visual field (64.7 versus 60.0%; $F_{1,22} = 8.29$, $p < 0.01$), and higher speed (64.0 versus 60.7%; $F_{1,22} = 6.82$, $p < 0.05$). Moreover, the experienced drivers gave estimates which were systematically closer to the theoretical values than were those of the beginners (71.5 versus 53.0%; $F_{1,22} = 13.95$, $p < 0.002$). The lack of effect of actual T_c duration was confirmed.

Three interactions were found. First, we noted a significant vision by speed interaction ($F_{1,22} = 9.77$, $p < 0.005$), which is shown in figure 3. Binocular vision produced better results only at the lower speeds ($F_{1,22} = 18.61$, $p < 0.001$), which, in our experiment, coincided with the shortest distances from the target. The interaction between driving experience and visual field which appears in figure 2a was only almost significant ($F_{1,22} = 4.23$, $p = 0.051$). The results of a Bayes-fiducial analysis (Rouanet and Lecoutre 1983) indicated that this interaction was not negligible, however. We therefore carried out an a posteriori test of the components of this interaction, and

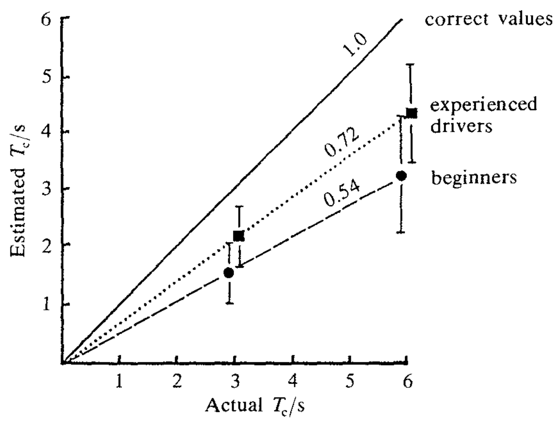

Figure 1. Relationship between the actual time-to-collision (T_c) and the mean of estimated values of T_c, together with standard deviations, for experienced drivers and beginners. Values on the visually-fitted lines indicate slope gradients.

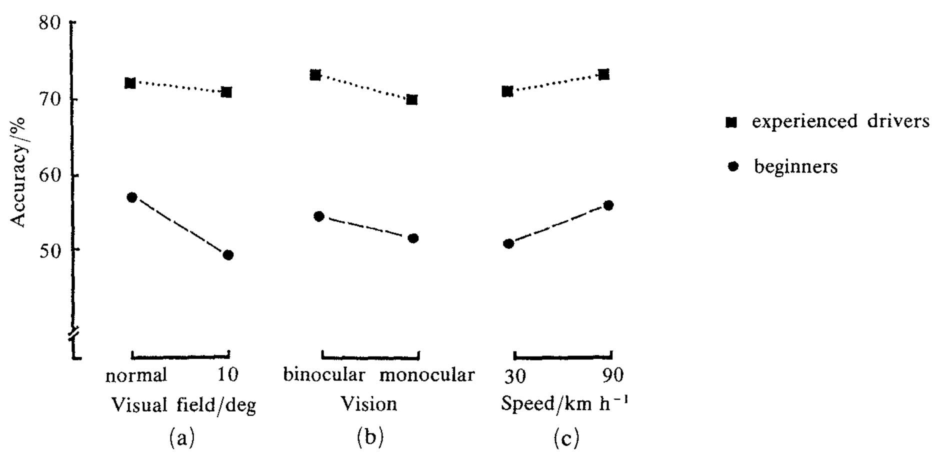

Figure 2. Mean percent time-to-collision (T_c) estimation for accuracy of experienced drivers and beginners under different conditions of (a) visual field, (b) vision, and (c) speed.

found that the normal visual field had an enhancing effect only for beginners ($F_{1,11} = 12.62$, $p < 0.005$), and not for experienced drivers. Lastly, further analysis showed that there was a significant interaction between speed and visual conditions ($F_{1,22} = 14.09$, $p < 0.005$): no speed effect was observed under normal visual conditions (normal visual field *and* binocular vision), whereas a significant difference in speed ($F_{1,22} = 26.04$, $p < 0.001$) was observed under visually impoverished conditions (restricted visual field *and* monocular vision).

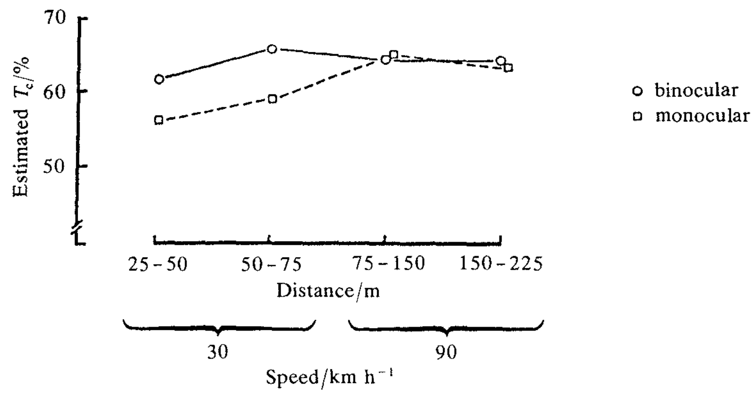

Figure 3. Effect of vision versus speed and distance from the target during viewing time, on the mean percent accuracy of time-to-collision (T_c) estimation.

4 Discussion

In this section we propose to discuss four main results, namely the significant effects of the factors (i) visual field, (ii) binocular/monocular vision, (iii) speed, and (iv) driving experience, and the interactions in which they are involved.

4.1 *Visual field*

The finding that the visual field had a significant effect on T_c estimation (see figure 2a) is quite compatible with the idea that speed information provided by the peripheral visual field is taken into account in the estimation of T_c. The subjects' estimation of the vehicle's speed seems to have been disturbed when visual information was reduced to the foveal or parafoveal field. Recently this kind of finding has been doubly confirmed, Groeger and Brown (1988) have shown, in a T_c estimation task, that narrowing the visual field to 10 deg (as compared to 40 deg) increases the error level. Furthermore, we have ascertained in a locomotor positioning task (Laurent et al 1988) that T_c is affected by decorrelation of the peripheral visual flow.

The fact that visual field had a highly significant effect with beginners and none with the experienced drivers is not inconsistent with our interpretation. On the contrary, it is in line with our hypothesis that differences in the level of subject skill may have resulted in the use of different strategies for obtaining T_c information. We shall return to this point later, in section 4.4. In any case, if only optic-flow information from the target object were used by the subjects, we would expect the results to be independent of the size of the visual field, since the target was visible and the target enlargement velocities were above threshold in all cases. On the other hand, a general enhancing effect produced by rich visual conditions, which is also compatible with the τ-hypothesis, might have been expected to pertain regardless of driving experience. Our results show that this was not the case. We are therefore inclined to attribute the visual field effect to the fact that the beginners assessed speed as a separate parameter.

4.2 *Binocular/monocular vision*

The superiority of binocular over monocular vision observed with both experienced drivers and beginners suggests that distance information provided by retinal disparity is also taken into account in T_c estimation. This was confirmed by the fact that binocular superiority was found only at lower speeds and with nearer targets (these two variables were not dissociated in our experiment). It is probable that this interaction predominantly involves distance rather than speed, since these data are in agreement with the operating range of retinal disparity, which is thought to be limited to about 100 - 135 m (Schiff 1980). Indeed, at 30 km h^{-1}, the target distances during viewing time were always less than this (and thus retinal disparity may have intervened), whereas at 90 km h^{-1} they were mostly larger. Nevertheless, on the basis of our results, which were obtained under dynamic conditions, the use of retinal disparity seems to have a lower bottom limit (about 75 m) than that suggested by Schiff (1980), working with static distance assessment conditions.

The mere processing of the target expansion rate (τ) cannot explain the improvement observed with binocular vision, since information on target expansion was available with both binocular and monocular vision. Even if we assume that the subjects' visual acuity for assessing target expansion may have been enhanced by binocular viewing conditions, we would then expect either an overall improvement of T_c estimates or binocular superiority under conditions where angular size change was very small (which was the case here at higher speeds and with more remote targets, see table 1). Our results show that this was not the case. On the contrary, they are compatible with the idea that distance information based on retinal disparity is used to estimate T_c.

4.3 *Speed*

The general effect of speed (ie more accurate T_c estimates were obtained at 90 km h^{-1}) was not found to pertain under the normal visual conditions (whole visual field and binocular vision) which served as reference conditions for the normal driving situation. The greater accuracy of the estimates produced at the higher speed must therefore have been due to interactions with factors related not to speed but probably to the impoverished visual conditions. The reason for these interactions is not evident. The information gained at higher speeds will obviously be particularly useful under poor visual conditions, but neither the type of information provided by higher speed nor the mechanisms compensating for the lack of visual information can be elucidated by our experiment.

4.4 *Driving experience*

Two principal differences between beginners and experienced drivers need to be discussed: (i) the systematically higher estimates produced by the experienced drivers, and (ii) the differences observed between the two groups of subjects in their sensitivity to visual conditions.

A large part—but probably not all—of the differences between the two populations might be due to the use of different decision criteria. It is thus conceivable that the varying degrees of underestimation observed may correspond to differences in the safety margin adopted by the subjects, depending on their skill level, ie depending on their ability to react and their knowledge of the spatiotemporal consequences of any braking or avoiding reaction (Spurr 1969). This suggestion is supported by the finding that the accuracy of the responses of both beginners and experienced drivers showed the same level of consistency.

Nevertheless, this explanation probably does not cover all the differences between the two populations. In view of the almost significant interaction between driving experience and visual field, we favour the hypothesis that differential use was made of visual information by beginners and experienced drivers. Indeed, although only the beginners seem to have taken into account the speed information contained in the peripheral visual flow, we established that both groups of subjects used distance information provided by binocular vision. These differences in response patterns, which need to be confirmed by further research, are compatible with the idea that different estimation strategies may be at work, depending on the skill level of the driver: beginners seem to use a method integrating speed and distance information, whereas experienced drivers seem to rely more on a method involving distance-change information. The use of the latter method by the experienced drivers appears to be quite plausible, in that the elimination of the speed parameter can be said to be very efficient. Indeed, it is well known, for instance, that visually induced speed sensations decrease as a function of exposure time ('speed adaptation': see Berthoz et al 1975; Denton 1980). Thus by relying on distance information, experienced drivers might use a more reliable type of visual information, for instance, one less sensitive to fatigue.

5 Conclusion

The results of our experiments conducted under actual driving conditions show that both speed and distance information are taken into account in T_c estimation. Furthermore, our findings suggest that these two kinds of information may be used differently depending on the skill level of the subject.

Even though the results of our experiment do not exclude the possibility that the optic variable τ, the target expansion rate, may have been used simultaneously—either primarily or secondarily—they cannot be explained satisfactorily in terms of this variable alone. Although it has been demonstrated that this information is theoretically sufficient, can be isolated in laboratory situations, and is reasonably useful on its own, there may well exist situations where other sorts of information are taken into account, particularly in real-life tasks where all kinds of information are available and where a high degree of accuracy is required.

Previous studies on the visual origin of T_c have usually analysed τ either independently or combined with other sources of information; the influence of these other sources was therefore not measurable. Because of the lack of any really incisive method, the method chosen here, which consisted of manipulating various information sources in real-life visual situations, seemed to be necessary in order to complement previous studies.

Although the studies based on an ecological optics approach favoured the processing of τ as the means of estimating time-to-collision, we acknowledge their contribution in stressing the importance of the information (such as τ) contained in the optic flow, which has for a long time been neglected. It is no longer possible, however, in a really ecological approach to vision, to neglect the other kinds of information provided by the visual system, the functional role of which still remains to be elucidated in many different self-motion situations. The fact that this information is taken into account—as demonstrated here—does not rule out the possibility that the optic variable τ may be the main or only method used, particularly in situations where no reliable information on speed and distance is available. This may have been the case in experiments conducted on simulated situations (McLeod and Ross 1983; Schiff and Detwiler 1979) and on plummeting gannets (Lee and Reddish 1981). The τ-method may also be favoured in emergency situations where T_c is very short, as in the case of emergency braking (Laurent et al 1987) or in avoidance reactions taken when facing a looming stimulus (see for example Schiff 1965). In any case, further experimental studies are necessary in order to determine under what conditions various kinds of information are used (conditions related for example to spatiotemporal constraints, the types of visual information available, or subject skill levels) and how they complement each other.

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References

Ball W, Tronick E, 1971 "Infant responses to impending collision" *Science* **171** 818-820

Berthoz A, Pavard B, Young L R, 1975 "Perception of linear horizontal self motion induced by peripheral vision (linear vection)" *Experimental Brain Research* **23** 471-489

Bower T G R, Broughton J M, Moore M K, 1970 "Infant responses to approaching objects: an indicator of response to distal variables" *Perception & Psychophysics* **9** 193-196

Brandt T, Dichgans J, Koenig E, 1973 "Differential effects of central versus peripheral vision on egocentric and exocentric motion perception" *Experimental Brain Research* **16** 476-491

Carel W J, 1961 "Visual factors in the contact analog", publication R61ELC60, General Electric Company Advanced Electronics Center, Ithaca, USA

Cavallo V, Brun-Dei M, Layo O, Neboit M, 1988 "Perception and anticipation in negotiating curves: the role of driving experience" in *Vision in Vehicles II* Eds A G Gale et al (Amsterdam: North-Holland) pp 365-374

Denton G G, 1980 "The influence of visual pattern on perceived speed" *Perception* **9** 393-402

Dunkeld J, Bower T G R, 1980 "Infant responses to impending collision" *Perception* **9** 549-554

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

Gibson J J, 1966 *The Senses Considered as Perceptual Systems* (Boston, MA: Houghton Mifflin)

Gibson J J, 1979 *The Ecological Approach to Visual Perception* (Boston, MA: Houghton Mifflin)

Godthelp H, Milgram P, Blaauw G J, 1984 "The development of a time-related measure to describe driving strategy" *Human Factors* **26** 257-268

Groeger J A, Brown I D, 1988 "Motion perception is not direct with indirect viewing systems" in *Vision in Vehicles II* eds A G Gale et al (Amsterdam: North-Holland) pp 27-34

Laurent M, Cavallo V, 1985 "Rôle des modalités de prise d'informations visuelles dans le pointage par positionnement du corps" *L'Année Psychologique* **85** 41-48

Laurent M, Cavallo V, Paul P, 1988 "How is gait visually regulated when the head is travelling faster than the legs" *Journal of Motor Behavior* **20** 301-316

Laurent M, Tournadre V, Bovet P, 1987 "Facteurs critiques du déclenchement du freinage d'urgence chez l'homme en situation de course" in *Recherches en APS II* eds M Laurent, P Therme (Marseille: UEREPS Université d'Aix-Marseille II) pp 223-234

Lee D N, 1974 "Visual information during locomotion" in *Perception: Essays in Honor of James J Gibson* eds R B MacLeod, H L Pick Jr (Ithaca, NY: Cornell University Press) pp 250-267

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

Lee D N, Lishman J R, Thomson J A, 1982 "Regulation of gait in long jumping" *Journal of Experimental Psychology: Human Perception and Performance* **8** 448-459

Lee D N, Reddish P E, 1981 "Plummeting gannets: a paradigm of ecological optics" *Nature (London)* **293** 293-294

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

Pavard B, Berthoz A, 1976 "Perception du mouvement et orientation spatiale" *Travail Humain* **39** 207-226

Purdy W C, 1958 *The Hypothesis of Psychophysical Correspondence in Space Perception* PhD thesis, Cornell University, Ithaca, NY, USA

Rouanet H, Lecoutre B, 1983 "Specific inference in ANOVA: From significance tests to Bayesian procedures" *British Journal of Mathematical and Statistical Psychology* **36** 252-268

Salvatore S, 1968 "The estimation of vehicular velocity as a function of visual stimulation" *Human Factors* **10** 27-32

Schiff W, 1965 "Perception of impending collision: a study of visually directed behavior" *Psychological Monographs* **79** whole number 604

Schiff W, 1980 *Perception: an Applied Approach* (Boston, MA: Houghton Mifflin)

Schiff W, Detwiler M L, 1979 "Information used in judging impending collision" *Perception* **8** 647-658

Spurr R T, 1969 "Subjective aspects of braking" *Automobile Engineer* **59** 58-61

Thomson J A, 1983 "Is continuous visual monitoring necessary in visually guided locomotion?" *Journal of Experimental Psychology: Human Perception and Performance* **9** 427-443

Warren W H J, Lee D N, Young D S, 1986 "Visual control of step length during running over irregular terrain" *Journal of Experimental Psychology: Human Perception and Performance* **12** 259-266

Yonas A, Bechtold A G, Frankel D, Gordon R F, McRoberts G, Norcia A, Sterfels S, 1977 "Development of sensitivity to information for impending collision" *Perception & Psychophysics* **21** 97-104