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The recording of eye movements/fixations is becoming a more and more popular tool in (applied) research, including traffic safety research. Obviously, this is a result of the more widespread availability of relatively easy-to-use apparatus to register eye movements. However, the question of what role eye fixations play in perceptual processing is not resolved. This paper reviews a number of traffic safety studies in which eye movement recordings were collected. For what research objectives has the collection of eye movements taken place? Special emphasis is given to the underlying - implicit or explicit - assumptions about the meaning of the eye fixations.

Introduction

The importance of the role of visual perception in driving seems seems evident and has often been stressed in the literature. In a recent Australian study it was concluded - again - that visual factors were the most prominent in the occurrence of traffic accidents (Cairney & Catchpole, 1991). Although notions, based on task analysis, common sense or normative grounds, exist about which information should be perceived in order to drive safely, it is not known which information is exactly used how, when and where by road users. It therefore seems a logical step to collect data on eye movements to gain insight in this matter. However, also various difficulties can be pointed at. Firstly, many of the eye movement studies have been done in research on reading, a quite structured task. One can wonder how driving in traffic resembles reading. In traffic many types of visual task are performed concurrently or serially; a driver can, for instance, be actively searching for certain information in finding their way (e.g. reading streetsigns) or merely 'looking around' searching no specific target. It can be assumed that in traffic eye movement behaviour is closer to viewing pictures than to reading. There are differences between reading and looking at scenes in terms of the characteristics of the stimulus. Such differences have implications for the way in which viewers scan the stimulus. It is also the case that the tasks of reading, picture viewing and search are quite different, and hence the generalizability from one situation to another must be questioned (Rayner, 1984). Moreover, both reading and picture viewing is usually performed under small visual angles, whereas in traffic almost 360° of visual angle is relevant. The research with nontextual stimuli indicates that the perceptual span is larger for pictorial stimuli than for text. It may be the case that different types of information are acquired from different regions, and also that the information is processed in a qualitatively different manner closer to fixation, but little is known about the nature of the information available within the perceptual span for nontextual material.

Another difficulty is that almost all recordings of scanning eye movements in this type of research on reading and viewing pictures have only considered the exploration of static scenes. It is not known what bias this has induced in the appreciation of the role of eye movements for the perception of the visual world. The fact remains that in real life a good deal of visual exploration occurs in a dynamic environment, and that many concepts developed from the analysis of static laboratory situations may not be very relevant to real life situations (Viviani, 1990). Of course, road users in traffic deal with both dynamic environments *and* dynamic observers.

Finally, there are difficulties, in theoretical as well as applied research, with the assumptions underlying the 'meaning' of eye movements. In this paper several of these assumptions are listed. The main part of the paper consists of a review of a number of empirical traffic safety studies in which eye movements have been registered.

Assumptions about the meaning of eye movements

Saccades are voluntary, quick, ballistic eye movements that take the eye from one fixation point to the next. The wide appreciation of volitional control has encouraged the use of saccades as overt indicators of otherwise hidden cognitive processes. But as Kowler (1990) states: "Reading thoughts from saccades is a dangerous business if it is assumed that where one looks, or how long one looks in a given place, is completely a function of choice of interest, independent of the constraints imposed by the saccadic programming apparatus itself. On the other hand, equally troublesome would be a search for invariant relationships between the visual stimulus and saccades under the assumption that performance is completely a function of the stimulus configuration, ignoring the contributions of voluntary choice, selective attention, and expectations" (p. 47). So, what can we learn from eye movement data about the cognitive and perceptual processes involved in the exploration of the visual world? There are several serious difficulties with the assumption that mental processes can be inferred inductively on the sole basis of experimental findings about eye movements (Viviani, 1990).

It is often assumed that the location of an eye fixation is related to the direction of attention. In line with this assumption some investigators assume that attention is always locked to fixation; they regard the movements of the eye as the movements of attention. It seems evident that the two ways of directing are at least related to eachother, but a one-to-one relationship can be questioned. There is much empirical evidence that the direction of attention and the position the eye is pointing at need not necessarily coincide (e.g, Posner, 1980). It appears in fact that, under appropriate conditions of pre-cueing, visual attention can be directed almost everywhere in the visual field, irrespective of the actual direction of the line of sight (Viviani, 1990). Moreover, there is at least some evidence that the direction of attention can - continuously or abruptly - change during an eye fixation. Van der Heijden (1992) suggests that covert attention, in cooperation with higher order processes, determines whether, and if so where, the eye has to move. "The starting assumption is not that the eye as a spotlight and attention as a spotlight complement each other in the sense that now the one, then the other perform the job. The starting assumption is that the eye and its movements and attention and its 'movements' have different functions and that they complement each other in the sense that both overt orienting and covert orienting are involved in performing the job; that there is not redundancy or duplication but a real cooperation or collaboration" (p.122). In Van der Heijden's view, a (saccadic) eye movement is just another response that can be given temporal priority by attention. If attention can perform its temporal ordering function in agreement with the quality requirements of the total information processing system, no overt eye movement is called for. If processes, responsible for the performance of one or another type of task, complain about the quality or spatial grain of the visual information they are supposed to work upon ('cannot read it') an eye movement is called for (see also Van der Heijden & Hagenzieker, 1992).

Selective attention can be moved about without saccades, but the reverse - the question of whether saccades require corresponding attentional shifts - is less clear. Klein (1980) did conclude that saccades could be made without shifts in attention, but his interpretation of results can be questioned (Kowler, 1990, p.59). A related assumption is that mechanisms of attention regulate the preparation and execution of a saccade; attention shifts are assumed to be programs for eye movements, in the sense that attention precedes the eye movement to the target location (Klein, 1980; Groner, 1988).

An closely related assumption is that eye movements are often taken as indicators of cognitive activity, the assumption being that what the eye is looking at testifies to what the mind is making of what the eye is looking at (Gonzalez & Kolers, 1985). The implication is that the location of a fixation testifies to the semantic aspects of the processing of the material fixated. Gonzalez and Kolers support the view that the location of fixations merely identifies the regions of the scene from which stimulation is derived, whereas the semantic or interpretative components are carried out subsequently on those inputs.

There has been a great deal of speculation concerning the factors that control eye movements in complex cognitive tasks such as reading, search and picture perception. Although the proposed models differ in a number of ways, the major distinguishing characteristic of the models is the relationship between ongoing cognitive activities and the duration of fixations and the length of saccades. At one extreme, 'global control models' view the details of eye movements as having almost no relationship to ongoing cognitive processes. There does not seem to be much support for this view. A second class of models, 'indirect control models', posit that the eye movements are only indirectly controlled by cognitive processes either via a memory buffer or via preprogramming of eye movements. The third general class of models, 'direct control models', suggest that the decisions of how long the eye is to remain at a fixation and where to move next are controlled by information extracted from the material (text) processed on the current fixation (Rayner, 1984; Groner, 1988).

Circular argumentation

Much of the faith in the possibility of investigating higher cognitive processes including attention via the analysis of eye movements rests on the identification of the information acquired by the observer with the visual stimulation that impinges on the retina (Viviani, 1990). The sequences of fixations are supposed to provide us with both the input stimuli and the overt ongoing response of the cognitive processes to these stimuli. However, from the fact that a given point of the scene has been fixated we can only infer that some information *might* have been picked up. So, the problem for interpreting eye movement data is that we should have the knowledge of the architecture of the very same underlying cognitive processes that we wish to clarify; we seem to be trapped in a circular argument. An example of this type of circular argumentation is found in the proposed relationship between the distribution of fixations and the distribution of 'informativeness' within the scene (see e.g. Antes & Penland, 1981). Although the term 'informativeness' is possibly the lowest common denominator one can find between the widely different stimulus aspects, it is highly circular in the sense that it is a word for what it should explain (Groner, 1988). Moreover, measuring what meets the fovea is only a part of what meets the (mind's) eye, and the acquired visual information cannot be measured reliably (Viviani, 1990).

The 'scanpath' assumption

The initial impetus for the scanpath theory came from the welldocumented fact that, during extended exploration of a scene, the observer's eye repeatedly returns to the same elements in the picture (Yarbus, 1967). This observation was followed up and formulated by Noton and Stark (1971) as the 'scanpath hypothesis'. They suggested that when confronted with a new stimulus, a particular sequence of fixations, called scanpaths, will occur which will reoccur when the same stimulus causes recognition. The scanned information is stored as a sequence of foveal details, linked by traces of the eye movements which would restore their original position in space. This memory scheme was called a 'feature ring'. No subsequent researcher ever found as clear-cut a result as Noton and Stark's. Groner (1988) summarizes several of his own studies in which he concluded that scanpaths are to a very large degree subject-specific, and therefore not very useful for a general theory.

The assumption of seriality

It is obvious that eye movements represent a strictly serial behavior. Thus, to posit a close connection between this overt behavior and some identifiable cognitive process amounts to postulating that at least the most significant aspects of these processes unfold sequentially in time. There is more and more evidence, however, that in perception several parallel processes act at the same time (see e.g. Rumelhart & McClelland, 1986). How then should the sequential eye movements be interpreted? They could be related to just one of the component processes rather than to the total event, or could be subserving, on a time-sharing basis, several distinct processes at the same time. In neither case would one be justified in claiming that 'the experimentally accessible quantities' can be used to 'understand the underlying processes of cognition' (Viviani, 1990).

Eye movements in traffic safety research

Fourteen empirical traffic safety studies in which eye movements had been collected, have been selected to get an indication of the type of research conducted in this area. Articles from different sources have been selected (e.g. conference proceedings, journal articles, research reports), and most of the studies are reported fairly recently. No attempt has been made to obtain a representative sample, since the review has the nature of a (small scale) pilot study. Special emphasis was given to the implicit or explicit assumptions encountered in these eye movement studies. Furthermore, data were collected concerning the research objectives, independent variables, other dependent variables than eye movements, registration of eye movements, the task and number of subjects, and research environment (laboratory, real life).

Assumptions

Many assumptions were expressed either explicitly or implicitly; they are shortly summarized below. In all, half of the studies mention the assumptions explicitly, the other half only implicitly. The assumption encountered most often is that the information looked at will always be further processed. Sometimes (e.g. Luoma, 1991) it is considered a problem of the "eye movement methodology that any further processing of the information remains unregistered" (p. 326); therefore also other measures than eye movements were taken by Luoma. The 'processing assumption' is sometimes accompanied by the additional assumption that the longer the duration of the eye fixation, the more or deeper the information is processed (Miura, 1990; Wierda *et al.*, 1990). Also it is often assumed that it is most often necessary to fixate information to be able to process it further (e.g. Miltenburg & Kuiken, 1991), although it is often recognized that also peripheral vision is used while driving (e.g. Gallagher & Lerner, 1983). The closely related assumption of a linkage between attention and eye movements is explicitly stated in a number of studies. Usually the researchers are aware of the problems connected with this assumption (e.g. Noy, 1990); only once this assumption does not seem to be questioned (Erikson & Hörberg, 1980).

Another assumption as found in the reviewed studies is that eye movements are somehow related to what is called mental workload or driver workload (e.g. Verwey, 1991; Miura, 1990) or arousal (Unema & Rötting, 1990), resulting in more and shorter fixations 'on the road' and fewer on secondary tasks with higher workload; this would be accompanied by a reduced blink frequency (Hancock *et al.*, 1990).

Sometimes still other assumptions were encountered, such as that certain conditions lead to more 'adequate' eye movement behaviour than others. For example, adults or experienced drivers are considered to have 'better' strategies than children or inexperienced ones (e.g. Zwahlen, 1991; Wierda *et al.*, 1990); eye movement behaviour in daylight conditions is 'better' or 'safer' than during nighttime (Mortimer & Jorgeson, 1974); and the closer eye fixations are to brake lights the shorter reaction times to those lights a following driver will have (Sivak *et al.*, 1986).

What was the research objective and which independent variables have been used?

Specific hypotheses concerning (patterns of) eye fixations were encountered in four studies (Miltenburg & Kuiken, 1990; Miura, 1990; Unema & Rötting, 1990; Wierda *et al.*, 1990). The other ten studies were of a more exploratory nature. The various research objectives are reflected in the independent variables that have been chosen. Most often (10 times) traffic environments were varied (complex versus simple situations, busy versus quiet, daytime versus nighttime, various objects or signs, etcetera). Sometimes vehicle characteristics were varied, such as headlamps and brake light configurations (Mortimer & Jorgeson, 1974; Sivak *et al.*, 1986), or driving manoeuvres were varied (Hancock et al., 1990; Unema & Rötting, 1990). In four studies experienced drivers or adults were compared with inexperienced ones or children (Miltenburg & Kuiken, 1990; Verwey, 1991; Unema & Rötting, 1990; Wierda *et al.*, 1990). In three studies a secondary task was variously used (Noy, 1990; Verwey, 1991; Hancock et al., 1990). In almost all studies the eye movement behaviour of car drivers was investigated; in one study bicyclists were the subject of study (Wierda et al., 1990). In one study no independent variables were used (Zwahlen, 1991).

Which dependent variables have been used?

In most studies two dependent variables (5 times) were used or more (4 times). Besides eye movement/fixation data, reaction time (in 4 studies), head movements (3), speed or other driving behaviours (3), workload questionnaires (3) or other variables were measured. Only occasionally other measures than eye movements were collected *because* of the problems concerning the underlying assumptions about the interpretation of eye movement data (Gallagher & Lerner, 1983; Luoma, 1991; Noy, 1990). In five studies only eye movement data were collected (Miltenburg & Kuiken, 1990; Erikson & Hörberg, 1980; Mortimer & Jorgeson, 1974; Zwahlen, 1991; Sivak *et al.*, 1986).

Task and number of subjects

The number of subjects varied from 1 (Rahimi *et al.*, 1990) to 75 (Luoma, 1991). Mostly between 5 and 25 subjects were used. In ten studies the task of the subject consisted of real driving in a real life environment, sometimes they had to perform an additional secondary task. In the other studies the subject drove a simulator (Noy, 1990), pretended to ride a bicycle while seated at the passenger's seat of a van (Wierda *et al.*, 1990), watched video pictures (Miltenburg & Kuiken, 1990) or answered questions while looking at static slides (Gallagher & Lerner, 1983).

How have eye movements been recorded?

In most studies (10) eye fixations were recorded by using the cornea reflex method. Usually the output from a television camera viewing the corneal image is electronically mixed with the output from another camera viewing the scene that the subject is looking at; the resulting display, has a bright spot at the point in the field of view which the subject is fixating at any moment (see Carpenter, 1988). Since this method is quite sensitive to head movements, the equipment is usually mounted on a helmet which moves with the subjects' head.

In three studies (Verwey, 1991; Hancock et al., 1990; Rahimi et al., 1990) eye movements were collected by means of direct viewing of video pictures. Simply observing a subject's eyes one can detect crude movements, for example to the left, right, up or down.

In one study electro-oculography (EOG) was used (Noy, 1990). Electrodes placed in the region of the eyes register potentials that change in synchrony with their movements. However, this method has a number of drawbacks. It is for instance not clear what the origin is of the corneoretinal potential. Moreover, the potentials also change when an eye movement is planned but not executed (Carpenter, 1988).

Which type of conclusions has been derived?

In general, large effects of road geometry and other situational characteristics were found in all fourteen studies. Also strong individual differences were reported quite often; and (smaller) effects of 'workload' (usually coinciding with traffic environment), vehicle characteristics, or driving manoeuvres were found. The conclusions are often reported in terms of frequency and duration of eye fixations, and sometimes in terms of fixation sequences. But how should these findings be interpreted? Should one be satisfied with "results that are in line with common sense"? (Erikson & Hörberg, 1980).

Discussion

As stated in the introduction many assumptions about the meaning of eye movement (fixations) have been expressed but it is still not clear how (and whether) they reflect underlying processes, such as attention. It was hypothesized that studies in which such assumptions have been explicitly taken into account and in which 'precautions' were taken, in the form of e.g. additional dependent variables, would come up with the most useful results. In general, it seems indeed that when no specific hypothesis is formulated and eye movements are the sole dependent variable, the results obtained are hard to interpret. And conclusions in terms of frequency and duration of fixations are difficult to interpret without assumptions about their meaning. So, while the validity of underlying assumptions about the meaning of eye movements can be questioned they also add - when explicitly taken into account - to the understanding of the processes being investigated. Therefore, the research objective should not only be formulated in terms of e.g. distributions of eye fixations or other quantitative parameters of eye fixations, but also in terms of content-specific interpretations. Besides, assumptions and research objectives, however, also other factors seem to play a significant role.

An important factor seems to be the *task* the subjects had to perform during the experiment. In many cases the task of the subject was 'to drive a car as normally as possible' without further instruction. This seems to lead to strong individual differences which in turn result in non-significant effects of experimental conditions. By using a more specific (additional) task - e.g., "which sign did you see?", cf. Luoma (1991); or "should you stop at this crossing or not?" cf. Wierda *et al.* (1990) - the investigator can determine beforehand at what locations the 'relevant' eye fixations should be analyzed. This specific task has another advantage in that also *additional dependent variables* (percentage correct, reaction time) can be measured in combination with the eye movements. Also because of the strong individual differences in eye movement behaviour, a considerable *number of subjects* is needed to be able to find significant effects of experimental conditions. Furthermore, the use of *controlled independent variables* adds to the interpretability of the results. This is not always easy to establish since almost all studies were conducted under 'real life' conditions. When differences between traffic situations result in different eye movement patterns or durations one can often not tell which differences contributed to this effect. When, for instance, 'crowdedness' was varied (Miura, 1990), besides traffic density also the geometry of the road environment and the driving speed covaried.

In many of the reviewed studies some but not all of these 'prerequisites' are met. The following examples serve to illustrate this. Sivak *et al.* (1986) investigated eye fixation locations of drivers following a lead car. They formulated the explicit assumption that it would be safer when fixations are located closer to the position of the brakelights than when they are farther away from the brakelights, because the driver would be able to react faster to them. They measured eye fixations, but not reaction time; the latter could have resulted in stronger conclusions than they were able to derive with the eye fixation data. A second example is a study by Miltenburg and Kuiken (1991) who investigated eye fixations of experienced and inexperienced drivers while they were watching various recorded traffic situations on a tv-screen. There was no specific task instruction and due to strong individual differences, no statistically significant effects were found. And Zwahlen (1991) collected eye movements of nine experienced drivers while they were instructed to drive through a number of curves as they would normally do. Zwahlen did not use independent variables (he wanted to compare the observed eye movements with formal rules about looking behaviour). His conclusion was that "there appears to be no discernible simple systematic eye fixation sequence pattern within and between the runs of a single driver, as well as between the runs of different drivers" (p. 182).

The state of affairs in theory about visual perception, and the meaning of eye movements in particular, is reflected in the nature of the reviewed studies in the area of traffic safety: most were of an exploratory character. At the same time a tendency exists to strive for 'ecologically valid' research, in which real driving in real traffic environments is studied. This is probably encouraged by the available advanced eye movement registration equipment, although the ecological validity of driving around with a helmet (which reduces at least part of the peripheral vision) can be questioned. The suggested 'prerequisites' concerning the research design for studying eye movements in traffic possibly pose (additional) limitations to the much strived for 'ecological validity' of the research in this area, but they are expected to lead to better interpretable, theoretical sound results and applicable results, particularly when these studies in traffic safety research are conducted in line with current knowledge about accident data and driving behaviour.

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