MANIPULATING OPTICAL LOOMING TO INFLUENCE PERCEPTION OF TIME-TO-COLLISION AND ITS APPLICATION IN AUTOMOBILE DRIVING

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Direct manipulation of optical looming provides convincing evidence of the contribution of optical looming in estimating time-to-collision (TTC). Precise manipulation of optical looming cues can be easily accomplished through computational scaling of (real or virtual) objects without impinging upon the naturalness of the task. This paper first discusses three ways to manipulate optical looming by scaling object size in order to influence perception of TTC. Then two principles affecting the implementation of optical looming manipulation are addressed. Next by revisiting the data of previous research, influences of knowledge about the optical looming manipulation and practice on the effect of optical looming manipulation are discussed. This supports our proposed principles and confirms the possibility of introducing the concept of optical looming manipulation into actual automobile design. Finally a potential application of optical looming manipulation, a dynamic brake light system, is proposed for automobile driving, to reduce the frequency of rear-end collisions. Issues in implementation of such a system and future research to validate it are also identified.

INTRODUCTION

Optical looming, defined as the symmetrical expansion of the retinal image size of an approaching object on a collision course, is an important cue for the perception of *time-to-collision* (TTC) (Lee, 1976). As evidence of this, a direct relationship between optical looming and control of locomotion has been found, for example: in animals running towards a virtual size-changing solid circle displayed on a computer monitor (Sun, Carey & Goodale, 1992); for real and virtual ball catching involving dynamic size changing (Savelsbergh et al., 1991, 1993; Wann & Rushton, 1995A); for braking while approaching a virtual size-changing barrier in a bicycling simulator (Sun & Frost, 1998); and for braking behaviour while following a size-changing lead vehicle in a simulated car driving experiment (Li & Milgram, 2004). In those studies the optical looming cues which naturally occur during approach were manipulated in real time, and it was found that, in general, initiation of subjects' actions (e.g. braking or grasping) is accelerated or delayed when responding to an approaching target whose size is being artificially expanded or contracted. Those results further confirmed the important role of optical looming in the perception of TTC, and thereby the control of any behaviour dependent on it.

In the particular field of automobile driving, research has shown that drivers are able to control braking based on TTC information perceived from optical looming (van der Horst, 1990, 1991; van Winsum & Heino, 1996). For judgements about when to brake, how hard to brake, or whether it is necessary to brake at all, the following driver (FD) is able to rely on two principal cues: lead vehicle (LV) brake lights and direct visual information about how rapidly the following vehicle (FV) is closing in on the LV. Whereas in most circumstances such directly perceived information may be adequate, in more extreme situations, such as emergency braking, it is clearly not adequate, because there is always a danger that the FD will not adjust his braking to a high enough level in time if the LV happens to have braked very suddenly and very hard.

The braking response – moving the foot to the brake pedal – is only the first stage. The braking adjustment stage is just as critical. Normally a FD does not initiate full-power braking as soon as he sees that a LV is braking since, among other things, this would risk being run into from behind. Rather, drivers normally adjust their braking on the basis of the perceived urgency of the situation. In an emergency, however, it is important, and often critical, to adjust braking to an appropriate level early enough, because the sooner deceleration is initiated, the more effective it is.

Unfortunately, rear-end collisions can occur if the FD interprets the LV's movement incorrectly and ends up with too little time to respond adequately. This can occur, for example, if the FD perceives a stopped LV as a moving LV, or perceives a rapidly braking LV as a slow braking LV. Such occurrences may be due to optical expansion adaptation (Gray & Regan, 1999, 2000) or insufficient information provided by the current brake lights. According to the 2002 General Estimate System (GES) and Fatal Analysis Reporting System (FARS) in the USA, the most recent year for which data are available, rear-end collisions accounted for almost one-third (1.9 million) of all crashes and caused 5.2% (1,987) of total fatal crashes, 29.6% (0.57 million) of total injury crashes and 30.5% (1.328 million) of total property damage only crashes.

In light of the discussion thus far, a potential application has been suggested involving manipulation of optical looming in automobile driving to reduce the rate of occurrence of rear-end collisions (Li & Milgram, 2004). If a feasible and effective way can be found to suitably manipulate the optical looming cues which naturally occur during approach towards a LV for actual vehicles on the road, introduction of this concept could cause a significant number of following vehicles (FV) to brake sufficiently sooner to have a practical impact on automobile safety statistics. The proposed concept is based on the hypothesis that exaggerating the rate of optical looming whenever a LV brakes very hard and/or when lead distances become very short will intuitively provide the FD with the illusion of an (artificially) quickly approaching LV, which may then prompt the FD to decelerate as soon as possible, before it becomes too late. Clearly, a decrease of even several milliseconds in braking time could have a significant impact on overall traffic safety, when aggregated over the extremely large number of FV braking incidents.

This paper first reviews some of the means used in earlier research to manipulate optical looming, and thus, presumably, manipulate the perception of TTC. A set of principles which govern such manipulations is then presented as a result of this review. Next, on the basis of revisiting data from the driving research of Li & Milgram (2004), we discuss the potential influence of factors such as practice and knowledge about the manipulation on the effect of manipulating optical looming. Clearly such factors must be considered if the concept in question is ever to be applied for real driving. Finally the potential for manipulating optical looming in real vehicles is explored, resulting in a proposal for a dynamic brake light system. In conclusion, further research to validate this concept is recommended.

REVIEW OF METHODS FOR MANIPULATING OPTICAL LOOMING

Manipulation based on *steady rate of size change*

In the simplest case, optical looming of an approaching object can be directly manipulated by continuously increasing or decreasing its size. For example, in Savelsbergh's experiments involving the catching of a steadily deflating ball, during its flight the ball was deflated from a diameter of 7.5cm (Savelsbergh et al., 1991) or 8cm (Savelsbergh et al., 1993) to 5.5cm, at a calculated steady rate of deflation. If the intention in such an experiment were to present a *constant delay* in TTC through manipulation of optical looming, then it can be shown that physically deflating the ball at a constant rate would actually reduce the diameter too rapidly during the early stages of flight, resulting in a much longer perceived TTC than intended. Furthermore, in the latter stages of flight, the optical size would result in rapid looming, equivalent to a sudden decrease in apparent TTC (Wann & Rushton, 1995B).

Manipulation based on *displacement of distance*

A second, more precise way to manipulate optical looming is to mimic the retinal image expansion of the same fixed size approaching target, *as if it were located in front of or behind its actual position*. Although such a manipulation can clearly not be carried out for actual real world objects, it can easily be realised for virtual objects in a computer simulated environment. For each frame during approach, the software can recompute the size of the target, and then draw a scaled version in accordance with the distance between the observer and the target. The simple algorithm one can use is that R, the factor scaling the rendered size of the target, should be changed for each frame, such that (Wann & Rushton, 1995B):

$$R(t) = [Z(t) / (Z(t) - D)]$$

where $R(t)$ is the resulting time dependent target scale factor; $Z(t)$ is the instantaneous distance between the observer's viewpoint and the target; and D is the equivalent distance selected to manipulate the target during approach. Note that D here represents the *virtual* distance corresponding to the target's relative rate of expansion; in other words, the target is not really displaced by the distance D. If D is positive in the equation, then the effect is as if the LV were displaced to be *closer* to the observer during approach. Conversely if C were to be made negative, then the effect is as if the target were displaced to appear *farther away* from the observer during approach.

In the experiment mentioned earlier involving a gerbil running towards a size-changing virtual solid circle on a computer screen (Sun, Carey & Goodale, 1992), the diameter of the target circle was manipulated in such a manner as to mimic the optical looming of a constant 3cm diameter circle located 7.5cm *closer to* (for expanding trials) or 7.5cm *behind* (for contracting trials) the actual position of the target screen.

In their experiment to investigate braking in response to a rapidly decelerating lead vehicle (LV) (Li & Milgram, 2004), the size of the LV was expanded to mimic the same LV of constant size, but with a relative rate of expansion as if the LV were located 4.444m in front of its actual position. In a similar earlier experiment involving braking toward a stationary barrier in a bicycle simulator, manipulation was also based on displacement of distance (Sun & Frost, 1998).

While manipulating optical looming based on the displacement of distance principle, the actual offset (i.e. delay or advance) in theoretical perception of TTC will vary during the approach according to the relative speed between the observer and the target. (In particular, the magnitude of the TTC offset will equal the displaced distance, D, divided by the instantaneous relative speed.) If the object being approached is stationary, or if an object is approaching a stationary observer, for a constant speed approach manipulation based on constant distance displacement should produce a constant offset in perception of TTC. For a decelerating approach, however, with the decease in relative speed, a bigger offset in TTC will be produced for the same D.

For cases in which both observer and target are moving relative to each other, such as in the (Li & Milgram, 2004) braking experiment, the relative speed between the FV and LV usually follows a pattern of first increasing and then decreasing assuming that the FD successfully brakes behind the LV. This should result in larger decreases in perceived TTC at the beginning and the end of the braking process, with a smaller decrease in the middle. For example, given Li & Milgram's constant forward displacement during braking of D=4.444m, computed TTC offset varied theoretically between 200ms, for relative speed between LV and FV = 80km/h (speed of LV minus speed of FV), and infinity, when relative speed was zero.

Manipulation based on *displacement of time*

A third method of manipulating optical looming is to base it on displacement of *time,* by manipulating target size such that:

$$R(t) = [Z(t) / (Z(t) - RV^*\Delta T)]$$

where RV is the relative velocity between the observer and the target, and ΔT is the required time manipulation. In terms of the meaning of time-to-collision, we are considering here only the situation of an impending collision. (That is, if RV equals velocity of the observer minus velocity of the target, we consider only positive RV.) A constant advance or lag in TTC will be produced respectively by a positive or negative ΔT.

Because during approach this kind of manipulation produces a constant *time* offset, one consequence is that it should result in *continuously changing effective offset in distance* with a value thus depending on RV (RV*ΔT). In Wann & Rushton's (1995a) virtual ball catching experiment, for example, optical looming of the virtual ball during approach was scaled to provide a TTC estimate either 100ms earlier or 100ms later.

In conclusion, simple logic suggests that manipulation based on displacement of time has the advantage of being compatible with the original concept of manipulating optical looming to influence an observer's effective perception of *time to collision*.

GUIDELINES FOR IMPLEMENTING MANIPULATION OF OPTICAL LOOMING

While manipulating optical looming to affect a user's response behaviour, manipulation of the target's size has to be *imperceptible* for subjects, in order to exclude the possibility of adjustment of subjective risk criteria or any adaptation process. It is therefore necessary to plan one's experiment very carefully to avoid any *unnatural* change in target size which might catch the subject's attention. For example, when using the distance manipulation method, at the beginning of the manipulation some kind of a size “jump” should occur, involving an abrupt expansion or contraction of the size of the target, to mimic the retinal image of a constant size target located in front of or behind its actual location. One way to avoid this is the “gradual manipulation” approach adopted in Li & Milgram's (2004) experiment, in which the magnitude of distance manipulation was *gradually* increased from zero to the full distance over a period of 0.5s. Even when using time displacement manipulation, it is still necessary to be careful to avoid any conspicuous “swelling” or "shrinkage" in target size which might catch subjects' attention. This could result from large relative velocities between the observer and the target, especially for small relative distances (Z).

A second important decision is the choice of the magnitude of manipulation, as well as the maximum and minimum sizes to which the target can be allowed to be scaled, in order to avoid any conspicuous distortions of the target relative to its visual surround. On the one hand, either the distance or the time displacement has to be chosen to be not too small, so as to maximise the potential effect on subjects' reaction. On the other hand, they should be not too large, to ensure that the manipulation remains imperceptible. In Li & Milgram (2004), for example, 3 out of 11 participants had some awareness of the size manipulation after having sensed that, under some extreme conditions (for Z very small), the image of the LV sometimes appeared even larger than the width of the driving lane.

INFLUENCE OF KNOWLEDGE ABOUT MANIPULATION AND PRACTICE ON THE EFFECT OF MANIPULATION

It is obvious that, although manipulation of optical looming introduces a conflict into available visual cues, the intention is that this conflict be harnessed for useful purposes. Consequently, before considering its potential application, for example in real automobile driving, we must first understand how subjects' knowledge about the manipulation of optical looming might influence its effect. From the results of Li & Milgram’s (2004) driving experiment, for instance, where, as mentioned above, 3 of 11 subjects indicated that the image of the LV during braking appeared not normal, this did not necessarily mean that those subjects were specifically aware of the manipulation of optical looming. However, it might have caused them to suspect that the size of the LV provided non-veridical information, which might have caused them to depend more on other, perhaps weaker visual cues to control their braking (such as length of the road between FV and LV, as well as decreasing speed). We would therefore expect the effect of manipulation to be larger for subjects who do not notice any unnatural size change of the LV during braking.

In the Li and Milgram experiment, the same trials were repeated in 3 sessions, which were carried out on three successive days. By examining the braking profile day by day, it would be interesting to know how practice influenced the effect of manipulation, especially since subjects did admit to changing their following and braking strategies over the course of the three sessions. In addition, the three subjects who detected something abnormal pointed out that they started to perceive this only during the second or third day.

Figures 1-4 show respective results for time of releasing gas pedal, time of first pressing brake pedal, time of maximum braking force, and minimum following distance at the end of a braking event. These are shown for the three manipulation conditions: where the first, dotted bar is for manipulation starting at beginning of braking (MA); the second, vertical line bar is for manipulation starting before braking (MB); and the third, diagonal line bar is for no manipulation (NM). Each graph also shows results across the three days and for the two groups of subjects: “No” for the three subjects who thought the image of the LV appeared *abnormal* during braking; and “Yes” for the eight subjects who thought the image of the LV appeared *normal* during braking.

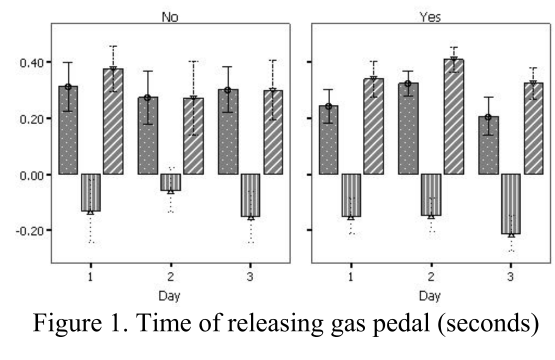

Figure 1. Time of releasing gas pedal (seconds)

As seen in Figure 1, for the 'No' group, there were almost no differences in time of releasing gas pedal between the second and third days (sessions) between NM events and MA events, which was confirmed by two paired t tests.

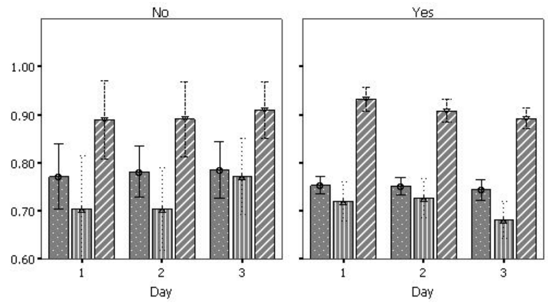

Figure 2. Time of first pressing brake pedal (seconds).

A larger difference between "Yes" and "No" groups is seen in Figure 2, a larger difference between time of first pressing brake pedal between MA and NM events could be detected for the "Yes" group relative to the "No" group.

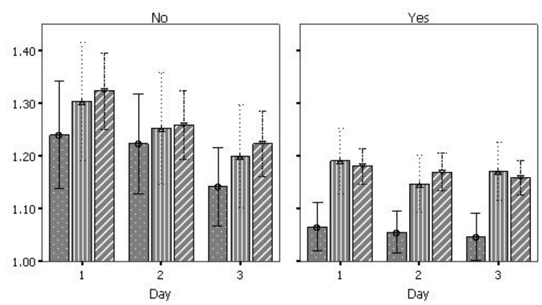

Figure 3. Time of maximum braking force (seconds).

As shown in Figure 3, we can see that (1) the 'No' group generally braked to maximum force later than the 'Yes' group; (2) the effect of manipulation was bigger for the 'Yes' group than for 'No' group, and (3) for the "No" group, participants seemed to brake to a maximum earlier with practice.

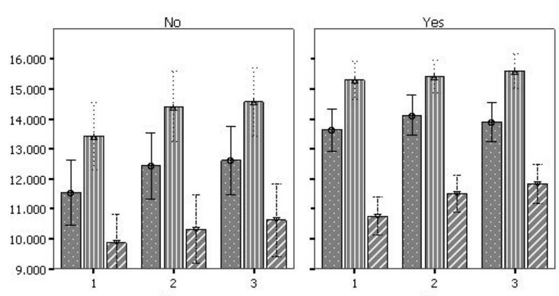

Figure 4. Minimum following distance (meters).

Finally, as to the minimum following distance, we can see from Figure 4 that: (1) with practice, both groups achieved longer minimum following distances, especially for the 'No' group; (2) the 'No' group stopped closer than the 'Yes' group; and (3) the effect of manipulation was bigger for the 'Yes' group, especially in the first and second day.

In summary, manipulation of optical looming appeared to produce a smaller effect on braking behaviour for subjects for whom the image of the LV during braking occasionally appeared abnormal. And they showed a bigger learning effect over practice, suggesting that their knowledge did reduce, but not eliminate, the effect of the manipulation. This emphasises the importance of the manipulation of optical looming being imperceptible and supports the potential to apply this concept in real automobile driving.

IMPLEMENTING MANIPULATION OF OPTICAL LOOMING IN AUTOMOBILES

In real driving situation, there is no obvious way to manipulate the size of a leading vehicle, as we could do with the virtual vehicle in the driving simulator. Research has shown, however, that the brake lights of a leading vehicle (LV) are a very important source of information for the following driver to regulate speed and inter-vehicle distance, on the basis of changes in the visible angle of the brake lights as well as their size and brightness. This is especially true during reduced visibility situations, such as night time, fog and rainy weather (Janssen et al, 1976; Liebermann et al, 1995). Theoretically then, it should therefore be possible to manipulate the optical looming of the image formed by the three brake lights, in order to influence FD braking behaviour. In fact, on the basis of a survey of research on rear signal patterns, Gail et al (2001) proposed a *two-stage brake force display,* in which area and luminance of brake lights would change from a smaller, lower luminance stage to a larger, high luminance stage for vehicle deceleration rates greater than $7m/s^2$. This is an example of trying to signal the emergent situation to following drivers (FD) by making use of ostensible "emergency" braking signals.

A similar dynamic brake lights system for reducing occurrences of rear-end collisions, as illustrated in Figure 5. Specifically, whenever the leading vehicle (LV) brakes rapidly and detects a following vehicle (FV) within a certain specified distance, the *separation* and the *size* of the brake lights of the LV will be expanded *continuously* and *gradually* to amplify the natural optical looming which occurs during braking. According to evidence accumulated thus far, this should shorten perception of TTC and cause the FD to brake sooner, as well as provide additional time for planning and action.

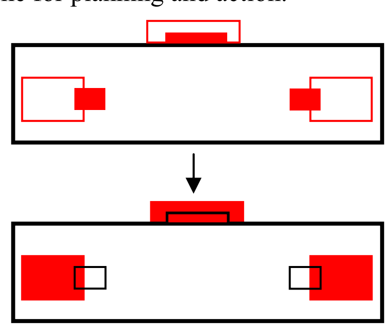

Figure 5. Proposed pattern of lights to be activated during normal braking. Bottom graph represents largest size and separation of brake lights, to which they are allowed to continuously and gradually expand from normal pattern during emergency braking.

With the help of sensor technology to acquire data about following distances and relative velocity, it is relatively straightforward to implement one of the three types of manipulation discussed in this paper. Regardless of which algorithm is chosen, manipulation has to be imperceptible and continuous during braking, and compatible with the space available at the back of the (lead) vehicle. If manipulation based on a steady rate of change is adopted, the average duration of hard braking actions should be estimated, to calculate the rate of manipulation increase based on the space available on the LV. Similarly, if distance or time manipulation is used, the magnitude of manipulation should also be carefully chosen to ensure continuous manipulation during braking, within the limitations of available space at the back of the LV. This clearly raises the issue of available space, which would impose a significant constraint on manufacturers' design freedom.

It also must be noted that this kind of manipulation would only apply during emergent braking of the LV. On the one hand, current brake lights are quite sufficient for slow and moderate braking. On the other hand, to avoid any adaptation and ensure effectiveness during hard braking, the question remains about how to proactively decide whether the upcoming LV braking event is going to be hard braking or not. One possibility is for the intention of the driver to be first inferred by the speed of motion of the foot, when moving from the gas to the brake pedal. A second source of information is the speed at which the brake pedal is actuated. Together the brake pedal force and sensed deceleration can serve as input variable in conjunction with the vehicle speed to identify an impending braking manoeuvre and thus trigger a manipulation of brake lights.

DISCUSSION

Our hypothesis is that significant effects on FD braking behaviour can be expected through manipulation of only brake lights, especially in reduced visibility situations, even though fewer optical looming cues can be manipulated. Such manipulations should not conflict with the rich variety of visual cues provided by real life driving, including additional vestibular sensations as well as audio cues from the traffic environment.

Although it is possible to test experimentally whether such a dynamic brake lights system could possibly be effective in causing drivers to brake sooner in emergencies, the question remains about whether such an effect might be reduced in the long term due to adaptation processes on the part of the driver. Our current conjecture is that a reduction in the effect is not expected, for the following reasons:

(1) By amplifying optical looming with an offset in perception of TTC, information about emergent braking situation is inherently “encoded” into the optical looming of the image of the brake lights, an effect which is observed also when naturally approaching an LV. Information about the intensity of braking would thus be provided subconsciously, intuitively and automatically, that is, high level learning for evaluating the information would not be required.

(2) This would provide a true coding of the brake force, with various manipulation patterns offered depending on intensity of the braking of the LV and the braking reaction of the FD.

(3) Relative to the frequency and magnitude of manipulation in our laboratory experiments, in real driving rapid braking and thus this kind of manipulation would occur very infrequently. In addition, the magnitude of any manipulation would be smaller due to the limitation of the vehicle size, thus making it less noticeable than in the experimental situations.

In summary, the concept of a dynamic brake lights system appears to be feasible and potentially effective for reducing the occurrence of rear-end collisions. Through improved brake lights, reductions in brake reaction times of as little as 100ms could contribute to a significant reduction in stopping distances for emergency braking manoeuvres, and thus lead to a reduction in the frequency of rear-end collisions as well as in the severity of the remaining collisions (Sivak and Flannagan, 1993).

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