AN EMPIRICAL INVESTIGATION OF THE INFLUENCE OF PERCEPTION OF TIME-TO-COLLISION ON GAP CONTROL IN AUTOMOBILE DRIVING

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Optical looming has been proposed as a potentially important cue for the perception of time-to-collision (TTC) in the control of locomotion. In this paper, an investigation is reported on how manipulation of the optical looming cue can influence the perception of TTC, and thereby braking behaviour, for automobile driving in a low fidelity simulator. Eleven participants were instructed to follow a leading vehicle (LV) and appropriately respond to the braking events of the LV, which occurred randomly at different deceleration rates. For some braking events, during braking of the LV, size of the LV was expanded without subjects being aware of it. Results showed that subjects braked sooner when confronting an expanding LV compared to a constant-size LV. The experiment supports the theory that drivers use TTC information derived from optic looming to control braking. Potential application of the results to possibly reduce occurrences of rear-end collisions in real automobile driving is also discussed.

INTRODUCTION

Whenever an observer is on a collision course with another object, the visual image of that object will expand symmetrically in terms of its retinal image size. The resultant *optical looming* effect is an important cue for the perception of time-to-collision (TTC) (Lee, 1976). Although other visual cues can theoretically provide the same information (most notably the ratio between the perceived distance to the object and its perceived velocity of approach), substantial empirical data suggest that optical looming is preferred over other factors in estimating TTC. One of these is the fact that observer actions seem to be geared directly to optical looming even when it provides non-veridical information. For example, previous studies have found that direct real-time manipulation (i.e. expanding or contracting) of the optical looming of an object during approach (e.g. ball catching and bicycle braking tasks) can influence (i.e. advance or delay) the behaviour of subjects when responding to approaching targets (Savelsbergh et al, 1991, 1993; Sun, Carey & Goodale, 1992; Wann & Rushton, 1995; Sun & Frost, 1998). The theory is that, when observers respond earlier to an expanding target, or later to a contracting target, this behaviour is a result of manipulation of the optical looming cue.

In automobile driving, drivers have to maintain a safe headway with respect to the lead vehicle (LV) to avoid rear-end collisions. While the LV is braking, other than using information from LV brake light activation, the following driver (FD) has to rely on direct visual information – i.e. optical looming of the retinal image of the LV – to judge how rapidly he is closing in on the LV, and thus when to brake, how hard to brake, or whether it is even necessary to brake at all (Liebermann et al, 1995).

The objective of the present experiment is to investigate whether and how manipulation of optical looming of the retinal image of the LV will influence perception of TTC, as inferred through the braking behaviour of FDs in a simulated automobile driving task. Specifically, we are investigating whether increasing the size of the LV, while it is decelerating rapidly, can make the FD brake sooner. Our hypothesis is that an increase in size of the LV during braking artificially amplifies the optical looming of the retinal image of the LV, and will therefore affect perception of TTC and thus drivers' braking behaviour. In limiting ourselves to rapid deceleration, manipulation of LV size occurs only when the LV brakes suddenly and/or forcefully. Equally important is that these manipulations be *imperceptible* for the FD, in order to exclude the possibility of the FD's adjusting his subjective risk criteria.

It is also important to point out that our research is focussing on the effects on subject responses of manipulation of visual cues. It is thus not strictly necessary at this point to simulate the driving task with high fidelity. Nevertheless, if our hypothesis is supported, introduction of the concept of TTC manipulation to actual vehicles on the road – for example, by manipulating separation and/or size of LV taillights, which is one of the primary cues used to regulate closure during night time driving (Janssen, Michon & Harvey, 1976) or other visibility reduced situations, such as foggy and rainy weather – might cause a significant decrease in FD braking onset times, and thus reduce the frequency of rear-end collisions. Clearly, a decrease of even a few milliseconds in braking time could have a significant impact on overall traffic safety, when aggregated over the millions of following vehicle braking incidents.

METHOD

Participants

Eleven paid male student volunteers participated in the experiment. They were 20-36 years old (mean 25.7; SD 5.5) with normal or corrected-to-normal vision and naïve to the purpose of the experiment. All had full Ontario (G) driver licenses, with 3.5-19 years of driving experience (mean 7.6; SD 4.6). Our reason for limiting the subject population to young male drivers was to give more power to our experiment, by allowing us to focus on optical cue manipulation factors. In doing so, any existing significant differences in braking behaviour between manipulation and no manipulation conditions could be more easily identified, without other variances caused by gender or age.

Apparatus

Experiments were conducted using a low-fidelity driving simulator, developed by York Computer Technologies of Kingston, Ontario, running on a normal PC under Windows XP. The roadway scene was projected onto a large screen (150 x 110 cm), using a commercial LCD projector (LitePro 620, Infocus Systems) at a distance of 150 cm from the subjects. The steering wheel and gas/brake pedal was a WingMan Formula Force GP from Logitech, a standard commercial game control device. Figure 1 shows a sample scene for this experiment.

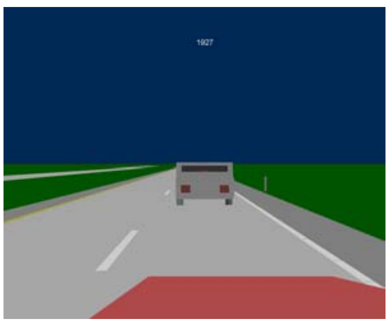

Figure 1. Experimental scene during LV following.
(The shape at the bottom is the hood of the following vehicle (FV). The number at the centre top is the current point total.)

Tasks

Subjects were instructed to "safely follow" (i.e. without overtaking) a LV at a required following distance on a simulated straight highway and appropriately respond to braking of the LV, just as they would "under real driving conditions". Subjects could control speed, steering, and braking. To control the prescribed following distance (either 22m or 33m), subjects were asked to maintain a gap equivalent to the distance between the posts along the right side of the road. Although a certain tolerance in following distance (±10m) was allowed, voice messages were given to help subjects stay within the proper following distance range. Whenever the following vehicle (FV) fell too far behind the LV, a message of *"Too far!"* was given; conversely, whenever the gap became too small, they were told *"Too close!"*.
Because braking behaviour depends on following distance and speed, we tried to keep these parameters approximately constant across braking events. In particular, the nominal speed of the LV was 80 km/h (a relatively complex algorithm, not explained here, was used to regulate LV speed; subjects were unaware of the details of this speed regulation), and a braking event was triggered only when the speed of the FV was within the range 77-83 km/h and whenever the following distance was ±1m around the prescribed following distance.
It is important to keep in mind that the focus of our research is on *perception of optical looming*, such that this was not meant to be a reaction time experiment. Because we did not want the subjects to brake hard every time, a range of different LV deceleration rates was used, in order that not all braking events would be "sudden".
To motivate subjects to attend to the task, not drive carelessly, and brake according to the instructions, a number of indices of performance were imposed. One was "excessive braking", caused by the following distance becoming too great during a braking event (1.5 x the proper following distance). Whenever this happened, a voice message declared "*Excessive Braking!*". The opposite case, of "insufficient braking" was manifested obviously in the form of a rear-end collision. Using a point system, whereby subjects were allocated 2000 points at the beginning of each trial, every time they received a voice message (i.e. "too far" or "too close") during driving, 10 points were deducted. Furthermore, for every second that subject strayed from the right lane (i.e. into the left lane or off the right edge of the road), another 10 points were lost. For every "excessive braking" profile, and for every "rear-end collision", subjects were docked 500 points. These points were averaged over trials and, based on the total points accumulated, a monetary bonus was awarded, to motivate subjects to follow the instructions.

Procedure

The study consisted of *18 trials,* comprising nine trials with a required following distance of 33.33m and nine at 22.22m. The 18 trials were conducted over four sessions, carried out on four successive days. During the first session, which was used for training, participants filled out a demographic questionnaire and received both written and oral instructions describing the experimental platform and the task. This was followed by two training trials. In each of the ensuing three sessions, participants completed 6 trials and filled out another questionnaire. At the end of the whole experiment, participants filled out one last questionnaire. All questionnaires probed the strategies used to follow the LV and control braking, and also solicited feedback about the experiment and the simulator.
At the beginning of each trial, a vehicle would pass the subject's vehicle in the left lane, move to the right lane ahead, and then become the lead vehicle (LV). During each trial, the LV randomly braked 25 times, using one of 7 different deceleration rates, as well as one of three different ways of manipulating the size of the LV. The deceleration rates were divided into 3 low rates: {2, 4, 6 m/s^2}, each of which occurred 3 times in a trial, and 4 high rates: {8, 10, 12, 14 m/s^2}, each of which occurred 4 times in a trial. The low deceleration rates were used as distracting events, to prevent subjects from habituating to hard braking. During high deceleration, the LV slowed to a complete stop, but during low deceleration, the LV slowed to only 60 km/h (from 80 km/h). In both cases the LV commenced reaccelerating to 80 km/h two seconds later.

Each trial lasted around 15 min and each session about 2 hours, including breaks (in addition to brakes!). Manipulation conditions and deceleration rates were randomised for every trial. The order of presentation of trials was counterbalanced across participants and sessions.

Manipulation of the Optical Looming Cue Through Size of Lead Vehicle (LV) During Braking

While the LV was braking, during some of the braking events the size of the LV was made to expand. The magnitude of the change was designed to mimic the retinal image expansion of the same LV, of constant size, *as if* it were located *in front of* the actual position of the LV – i.e. *closer to* the FV. For each frame during braking, the software recomputed the size of the LV, to be drawn in accordance with the virtual position of the FV. The algorithm was that R, the factor scaling the rendered size of the LV, was changed on each frame, according to (Wann & Rushton, 1995):

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

where $R(t)$ is the resulting time dependent LV scale factor; $Z(t)$ is the instantaneous distance between the subject's viewpoint and the rear of the LV; and C is the equivalent distance selected to manipulate the LV during braking. Note that C represents the *virtual* distance corresponding to the LV's relative rate of expansion; in other words, the LV is not really displaced by the distance C. (If C is made negative in the equation, then the effect is as if the LV is displaced to be further away from the FV during braking.) In designing the experiment C had to be chosen not too small, so as to increase the probability of observing an effect, but not too large, so as to ensure that the manipulation remained imperceptible. Through pilot studies on two subjects, using the method of limits to test the jnd with respect to LV size changes, C was set to a value of 4.444m.

Whenever $Z(t) \leq C$ (taking into account the length of the FV hood), the retinal image size of the expanded LV could become infinitely large, since the distance between the advanced LV image and the subject's eye would be effectively zero (even though the actual distance was not zero). In the experiment, to deal with cases of "infinite size", we simply set the largest LV size to be five times the original LV size.

To avoid the potential occurrence of a perceivable "jump" in the size of the LV at the beginning of the manipulation, we increased C, the magnitude of manipulation, *gradually,* from 0 to 4.444m during the first 0.5s of LV braking. To examine the potential effect of this gradual increase of C at the beginning of manipulation, we tested two methods of manipulation: *Manipulation starting At onset of braking (MA)* and *Manipulation starting Before onset of braking (MB)*. For MA, when the braking condition was met, the LV started both braking and size manipulation at the same time. However for MB, whenever the braking condition was met, size manipulation was triggered *first*, and only after full size manipulation (i.e. C=4.444m) was completed, did the LV start to brake. As mentioned, for both methods, MA and MB, the size manipulation transition lasted 0.5s.

Our reasoning in this design was that, if expanding the LV during its braking were to shorten the perception of TTC, generally the subjects should brake sooner on manipulation events (i.e. MA and MB) than on *No Manipulation* (NM) events. In addition MB events should elicit faster responses than MA events, since the full size manipulation was completed at the start of each braking event (MB) rather than 0.5s later (MA).

Data Analysis

Three performance indices were measured during subjects' braking (with 40ms resolution):

- *Time of taking Foot off Gas pedal (TFG).* This denotes the time between the beginning of the LV's braking and the moment of subject's complete releasing *gas* pedal.
- *Time of first Pressing Brake pedal (TPB).* This denotes the time between the beginning of the LV's braking and the moment of subject's pressing the *brake* pedal at first.
- *Time of Maximum Braking force (TMB).* This denotes the time between the beginning of the LV's braking and the moment of *maximum* brake force.

The other three recorded variables were

- *Minimum Following Distance (MFD)*, which denotes the distance between the LV and the FV when the LV started to reaccelerate after finishing a braking event;
- *Number of rear-end collisions*; and
- *Number of excessive braking events.*

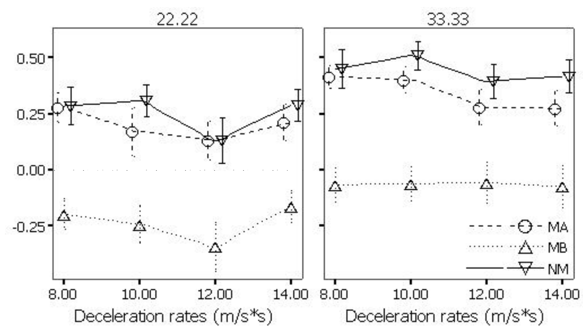

Figure 2. Time of taking foot off gas pedal (in seconds)
(In this and subsequent graphs, all results are across two desired following distances, 22.22 and 33.33m, and four deceleration rates, under three manipulation conditions. Error bars represent 95% confidence intervals. Positive, zero and negative times represent after, at, and before the start of LV braking).

RESULTS

Time of Taking Foot off Gas Pedal (TFG)

As shown in Figure 2, expanding the LV during its braking – i.e. MA & MB – did make subjects release the gas pedal earlier relative to the NM events. A three-way within-subjects ANOVA indicated a significant manipulation main effect ($F(2,130)=361.3$, $p<0.001$) without interaction with following distances and deceleration rates. Surprisingly, as seen in Figure 2 for MB events, subjects mostly took their feet off the gas pedal *before* the start of the LV's braking. After examining the braking profiles, it was concluded that one reason for this is that in some braking events, occasionally when the LV started to brake, the subjects were already decelerating in order to increase the headway to the desired level by taking their feet off the gas pedal (even pressing brake pedal in some cases). We found that this also happened in a few cases of NM and MA.

To explain the much earlier gas pedal release on MB events, the primary reason seems to be that subjects actually perceived expansion of the LV before its braking had begun, and responded to it by releasing the gas pedal (sometimes even pressing brake pedal as well), apparently in the belief that the LV was decelerating, even though its brake lights weren't (yet) on. Considering this possibility, after excluding the MB events, ANOVA still confirmed a main effect of manipulation ($F(2,130)=15.80$, $p<0.001$) without interaction with following distances and deceleration rates. However, paired-sample t tests revealed that TFG was not significantly shorter for MA than for NM events while following distance was 22.22m and deceleration rates were 8 and 12m/s^2.

Time of First Pressing Brake Pedal (TPB)

As shown in Figure 3, subjects pressed the brake pedal earlier on MA & MB events than on NM events. A 3-way within-subjects ANOVA confirmed a significant manipulation main effect ($F(2,130)=234.2$, $p<0.001$), but with an interaction between manipulation and following distance. Two 2-way ANOVAs were then conducted separately for the two following distances, producing significant manipulation main effects, without interaction between manipulation and deceleration rates. Paired-samples t tests for each following distance and deceleration rate among the MA, MB and NM events indicated significant differences, except between MA and MB for following distance of 33.33m and deceleration rates of 12 and 14m/s^2. When the following distance was short, subjects started to brake earlier on MB than on MA events. This was what we expected, since for MB the full manipulation was completed at the beginning of LV's braking. However when the following distance was long, this was reversed, because subjects had sufficient time after having released the gas pedal much earlier for MB events.

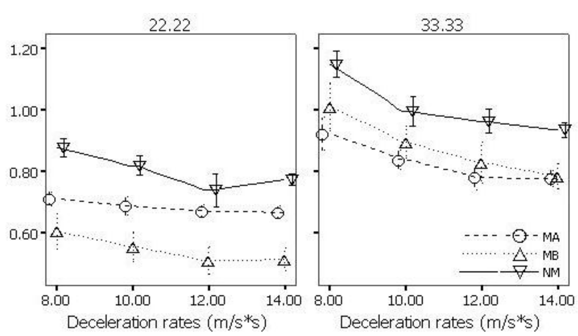

Figure 3. Time of first pressing brake pedal (in seconds)

Time of Maximum Braking Force (TMB)

As shown in Figure 4, subjects braked to the maximum force earlier on MA events than NM events. This trend is more obvious when the following distances were shorter and deceleration rates were faster. MB events basically fell between MA and NM events. A three-way within-subject ANOVA confirmed a significant manipulation main effect ($F(2,130)=42.6$, $p<0.001$), with an interaction between manipulation and braking deceleration, and an interaction between manipulation and following distance. Paired-sample t tests revealed significant differences in TMB between MA and NM events except when the following distance was 33.33m and the deceleration rate was 8m/s^2. With respect to the *magnitude* of the braking force, the average maximum force was lower for MB than MA events, since subjects usually started braking earlier on MB events. Both manipulation events (MA & MB) had lower forces than NM events. For NM events, only 13 out of 3168 braking events did not reach full brake pedal position; for MA, however, 30 braking events did not reach full position, and for MB there were 47 such events. This suggests that commencing braking earlier for the manipulation cases left a bigger margin of safety in terms of maximum braking force.

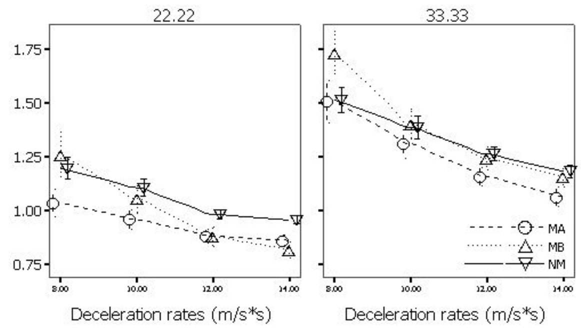

Figure 4. Time of maximum braking (in seconds)

Minimum Following Distance (MFD)

As shown in Figure 5, subjects achieved longer MFD after LV braking on MA & MB events than on NM events. In addition MFD for MB events was longer than for MA events. A 3-way within-subjects ANOVA showed a significant manipulation main effect ($F(2,130)=276.9$, $p<0.001$), with interactions among manipulation, following distance and deceleration rate. Paired-sample t tests indicted significant differences among MA, MB and NM events for each following distance and deceleration rate, except between MA and MB for the following combinations of distances and the deceleration rates: {8m/s^2, 22.22m}, {8m/s^2, 33.33m} and {10m/s^2, 33.33m}.

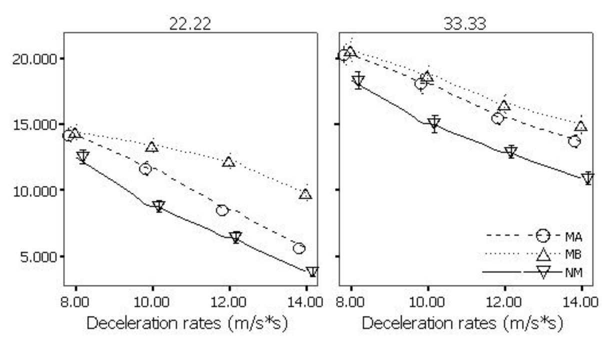

Figure 5. Minimum following distance after LV's braking (m)

Numbers of Rear-end Collisions and Excessive Braking

Out of 3168 braking events in this experiment, rear-end collision occurred 10 times. Of these, 6 occurred during the fastest deceleration rate for NM events. Excessive braking took place 4 times, two of which came from manipulation events during low deceleration rates. This result once again supports the effect of manipulation of the optical looming cue.

Questionnaire

At the end of experiment, the subjects were asked, "Did the LV image appear normal during braking?". Eight out of the 11 subjects said it appeared normal to them. However, 3 of the subjects said that sometimes the LV image appeared strange, with comments such as: "Occasionally the car swelled very large, even when it was still far away"; "Sometimes, it seemed larger than it should be" and "The car got too large as it came closer".

Another important question concerned the strategies subjects used to maintain a proper following distance and respond to the braking events of the LV. The subjects indicated that they used the following cues: expansion of the size of the LV; expansion of the size of the rear window of the LV; decreasing speed of the distance between the LV and the FV; speed of the LV passing the posts along the road; and speed of the LV passing the dashed centre lines. Although other cues existed in this driving simulator, and some subjects indicated they had used them, the strong results from the dependent variables tested suggest that braking behaviour was dependent mainly on the relative expansion rate of the size of the LV which was manipulated in the experiment.

DISCUSSION

The results reported here generally support our hypothesis: *subjects brake sooner while viewing a LV which is artificially expanding at a rate compatible with its being closer to the FV.* In particular, brake reaction times were at least 100ms faster, and gap distances when the FV came to a complete stop were about at least 2 m further away. This effect was most apparent for shorter following distances and faster LV deceleration. It is thus likely that information about TTC estimated from optical looming made a significant contribution to the control of braking in this task. Whenever the size of the LV was expanded, the naturally occurring looming of the LV retinal image was amplified such that the LV seemed closer to the FD, and thus speeded up subjects' responses to the braking of the LV.

With respect to the comparison of manipulation A and B, because subjects apparently responded to the expansion of the size of the LV *before* its braking, the effect of full manipulation versus gradual manipulation from the beginning of the LV's braking was masked, and thus can not be reliably compared from the present results.

As for the choice of magnitude of manipulation, although the 4.444m virtual forward displacement was undectable during the pilot studies, 3 subjects did detect that "something strange" had happened during the actual experiment. This did not necessarily mean, however, that those subjects actually detected the online manipulation of the size of the LV. In fact, it is more likely that they considered this as some technical problem with the simulator, especially for some of the more extreme situations. For example, whenever the following distance became very small (<2m), the size of the LV was expanded to 5 times its original size, an event which could very well be perceived as a "bug" in the software. Nevertheless, in our follow-up research, to make the manipulation more undetectable, we have reduced both the magnitude of manipulation and the maximum expansion of the LV.

In conclusion, our results have successfully shown that it is possible to reduce FD response times to a braking LV (especially a rapidly braking LV), although further research is needed with a high-fidelity driving simulator or a real driving situation, with richer visual cues and vestibular sensations to prove that this result can generalise beyond our low fidelity experiment. In actual driving, it may be possible to manipulate optical looming cues provided by some parts of the LV during rapid braking, such as the separation and/or size of the brake lights. Using gap estimation technology installed on the rear of lead vehicles, whenever a FV is approaching too quickly or is too close while the LV is slowing or stopped, the separation and/or size of the LV taillights could be progressively increased the closer the FV gets to the LV. The objective would be to ensure that the FD keeps a safe following distance, with the theory being that the system would act like a *visual amplifier*, in the sense that, when closing, the separation and/or size of the taillights would expand faster than the visual image of the LV and thus shorten the perceived TTC.

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