AN INVESTIGATION OF THE POTENTIAL TO INFLUENCE BRAKING BEHAVIOUR THROUGH MANIPULATION OF OPTICAL LOOMING CUES IN A SIMULATED DRIVING TASK

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This paper reports on an investigation of how manipulation of optical looming cues can influence braking behaviour, for automobile driving in a low-fidelity simulator. Twenty participants were instructed to follow a leading vehicle (LV) and appropriately respond to braking events of the LV, which occurred randomly and at different deceleration rates. During some braking events, the size of the LV was manipulated in different ways, without subjects being aware, in a manner concordant with the optical expansion that would have been observed during braking if the LV had been displaced to be closer or further away. Results showed that subjects braked sooner when confronting an expanding LV and later for a contracting LV, relative to a constant-size LV, to an extent corresponding to the magnitude of the manipulation. The experiment supports the theory that drivers use TTC information derived from optic looming to control braking.

INTRODUCTION

Whenever an observer is approaching another object, the resultant expanding retinal image of that object on the observer's eyes, or *optical looming*, is one of the important cues used for visual motor control, through perception of time-to-collision (TTC) (Lee, 1976). By expanding or contracting the retinal images of approaching objects, previous research has shown a direct relationship between the optical looming cue and performance, for tasks such as ball catching and bicycle braking toward a static obstacle. In particular, those results show that, when confronted with these size-manipulated approaching targets, observers responded earlier to expanding targets, and later to contracting targets (Savelsbergh et al, 1991, 1993; Sun, Carey & Goodale, 1992; Wann & Rushton, 1995; Sun & Frost, 1998). Because optical looming was the only cue being manipulated in those experiments, i.e. independently of other cues such as distance information, it has been proposed that the compensatory behaviour observed was a result of manipulation of the optical looming cue alone.

In a series of experiments to investigate whether manipulation of the optical looming cue in a simulated automobile driving task would similarly influence braking behaviour, we have found that following drivers (FDs) braked sooner while encountering a size-increasing lead vehicle (LV), in comparison to braking behind a size-constant LV (Li & Milgram, 2004a). More specifically, this behaviour was observed while following a lead vehicle (LV) whose size was manipulated during its braking, in a manner that created a retinal expansion of the same LV image, of constant size, but at a rate of change that corresponded to an *effective virtual displacement (EVD)*, that is, *as if* its actual position were closer to the following vehicle (FV) by a certain constant distance (just over 4.44 m in our first experiments), even though its actual position was unchanged.

One logical potential conclusion to infer from the above is that manipulation of the size of the retinal image of the LV influenced the FDs' perception of *time to collision* (TTC), since the algorithm used to realise the EVD corresponded to a theoretical computation of TTC. To explore this hypothesis further, an investigation was conducted to see whether not only *increasing* the size of the LV while it is decelerating during braking can cause FDs to brake *sooner*, but also, conversely, whether *decreasing* this size would cause FDs to brake *later,* in accordance with the magnitude of manipulation. Moreover, instead of introducing an *effective virtual displacement (EVD)* of the LV during braking as in our last experiment, the present experiment has instead used an *effective virtual time shift (EVTS)*, based on the same EVD magnitude used before (Li & Milgram, 2004b). The reasoning here is that an EVTS manipulation would be more compatible with the original concept of manipulating optical looming to influence an observer's effective perception of *time to collision (TTC)*.

One important issue raised in our previous experiment (Li & Milgram, 2004a) was whether the accelerated braking behaviour observed there might be a consequence not of EVD perception but simply of the occurrence of the amplified LV optical looming, which, even though consciously imperceptible, might have caused the FDs to drive more cautiously (i.e. brake sooner). Our principal hypothesis for the current experiment therefore was that FDs will not only brake *sooner* when encountering a size-*increasing* LV, but will also brake *later* when encountering a size-*decreasing* LV. Furthermore, the magnitude of such an effect should correspond to the magnitude of manipulation, in both directions. The idea behind decreasing the size of the LV during braking, in other words, was to artificially reduce the optical looming of the retinal image of the LV. If our hypothesis was true, this would support the role of optical looming in estimating TTC during locomotion. If, on the other hand, the simple presence of our manipulation were the cause underlying any modified FD braking behaviour, we would expect braking to be advanced (i.e. accelerated) for *both* the size increasing and size decreasing cases.

METHOD

Participants

Twenty paid male volunteers participated in the experiment. They were 20-36 years old (mean=26; SD=4.9) with normal or corrected-to-normal vision and naïve to the purpose of the experiment. All had full driving licenses, with 3-18 years of driving experience (mean 7.1; SD 3.9). Our reason for limiting the subject population to young male drivers was to give more power to our experiment, thus allowing us to focus on the optical cue manipulation factor. In doing so, any existing significant differences in braking behaviour between the manipulation and no manipulation conditions could be more easily identified, without 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 PC under Windows XP. The roadway scene was projected onto a large screen (150 x 110 cm) at a distance of 200 cm from the subjects, using a commercial LCD projector (LitePro 620, Infocus Systems). 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.)

Tasks

Subjects were instructed to "safely follow" (i.e. without overtaking) a LV at a required following distance (33m) 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. The engine sound of the subjects' vehicle was provided, with a frequency that varied with the vehicle's speed. A screeching sound would also be triggered whenever the FV braked very hard (deceleration $\geq$ 10m/s^2). Although a certain tolerance in following distance (±10m) was allowed during following, voice messages were given to help subjects stay within the required following distance range. Whenever the FV fell too far behind the LV, a message of “Too far!” was given; conversely, if 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, 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 required following distance. (A relatively complex algorithm, not explained here, was used to regulate LV speed; subjects were unaware of the details of this speed regulation.)

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 simple 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 (1.1 x required following distance). Whenever this happened, a voice message declared “Excessive Braking!”. The opposite case of 'insufficient braking' was manifested in the form of an obvious 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"), 20 points were deducted. Furthermore, for every second that subjects strayed from the right lane (i.e. into the left lane or off the right edge of the road), another 20 points were lost. For every "excessive braking" profile, and for every "rear-end collision", subjects were docked 200 and 500 points respectively. These points were averaged over trials and, based on the total points accumulated, a monetary bonus was awarded.

Procedure

The study was conducted in one session. First, participants filled out a demographic questionnaire and received both written and oral instructions describing the experimental platform and the task. This was followed by 2 training trials and 6 real trials. At the end of the experiment, participants filled out another questionnaire, which 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 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 5 different deceleration rates, as well as one of 5 different ways of manipulating the size of the LV. The deceleration rates were divided into 2 *low* rates: {2, 4 m/s^2} and 3 *high* rates: {6, 8, 10 m/s^2}. 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. In both cases the LV commenced reaccelerating to 80 km/h 2 seconds later.

Each trial lasted around 15 min and the whole experiment lasted about 2.5 hours, including breaks. Manipulation conditions and deceleration rates were randomised for every trial. The order of presentation of trials was counterbalanced across participants.

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 manipulated in one of two directions:

expansion or contraction, and at two levels: 200 and 400ms effective virtual time shift (EVTS). Specifically, the magnitude of the size manipulation was designed to mimic the retinal image expansion of the same LV, of constant size, *as if* it were located in front of (while expanding) or behind (while contracting) the actual position of the LV – i.e. closer to or further away from the FV. Note that *the actual position of the LV was not manipulated,* only its rate of change of size (optical looming). To provide an advanced or retarded EVTS for each frame during braking, the software recomputed the size of the LV, which was then scaled in accordance with the EVTS of the LV. The algorithm was that R(t), the factor scaling the rendered size of the LV, was recomputed for each frame, according to (Wann & Rushton, 1995; Li & Milgram, 2004b):

$$R(t) = [Z(t) / (Z(t) - RV(t) * \Delta T)],\ 0.5 < R(t) < 1.5$$

where ΔT is the required EVTS; $Z(t)$ is the instantaneous distance between the subject's viewpoint and the rear of the LV; RV(t) is the relative velocity between the FV and the LV (with RV(t) values positive for impending collisions and whenever $RV(t)<0$, $R(t)=1$). Note that $D(t)=RV(t)*\Delta T$ is the *effective offset distance,* or (continuously changing) virtual distance corresponding to the LV's optical expansion. Reiterating, the simulated LV is not really displaced by the distance D(t); only its rate of change of size is manipulated.

Positive or negative ΔT values produce the effects respectively of the LV being displaced to be closer to or further away from the FV during braking. How much the size of the LV is manipulated, R(t), depends not only on the constant ΔT, but also on the changing RV(t). During a typical braking event in this experiment, RV(t) gradually increases from about zero when the LV starts to brake (a braking event was triggered only when the speed of the FV was within ±3km/h of the LV's speed, 80km/h), then gradually decreases to zero whenever the FD successfully brakes behind the stopped LV. This actually makes the size manipulation smoother and limits it within a more moderate range, as compared to the EVD method was used in our first experiment (Li & Milgram, 2004a). Nevertheless, to avoid any conspicuous distortion of the LV relative to its visual surroundings, the largest (for expansion events) and smallest (for contraction) LV sizes were set to be respectively 1.5 and 0.5 times the original LV size ($0.5 < R(t) < 1.5$).

In designing the experiment, ΔT 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 consciously imperceptible. Taking into account the possible range of RV values, given the constraints of this experiment, five levels of manipulation (ΔT) were used: 0, ±200, ±400ms; in other words, where negative values correspond to retarded optical looming cues (LV effectively farther away), positive values to advanced displacement (LV effectively closer), and 0 to no manipulation. Our reasoning in this design was that, if expanding the LV during braking were to reduce the perception of TTC, the subjects should generally brake sooner on expansion events (+200 and +400 ms), and the opposite should occur for contraction events (-200 and –400 ms), relative to no manipulation events (0 ms). In addition, the magnitude of any effects should correspond to the magnitude of manipulation, with proportionately larger effects for 400 ms relative to 200 ms manipulations.

Data Analysis

The following indices were measured during each braking event (with 40ms resolution): Time of taking Foot off Gas pedal (TFG); Time of first Pressing Brake pedal (TPB); Time of Maximum Braking force (TMB); Maximum Braking Force (MBF); Maximum Relative Velocity (MRV); Minimum Following Distance (MFD); Minimum Time-to-Collision (MTTC); Number of rear-end collisions; Number of excessive braking events. For all time related indices, time was computed from the instant of LV braking.

RESULTS

Time of Taking Foot off Gas Pedal (TFG)

As shown in Figure 2, expanding (+200, +400ms) or contracting (-200, -400 ms) the size of the LV during its braking did make subjects release the gas pedal respectively earlier or later, to an extent corresponding to the manipulation levels relative to no manipulation events (0 ms). A two-way within-subjects ANOVA indicated a significant effect of ΔT manipulation ($F(4,116)=7.522$, $p<0.001$) but no significant effect due to deceleration rate ($F(2,118)=1.28$, $p=0.282$) and no significant interaction ($F(8,112)=0.363$, $p=0.938$).

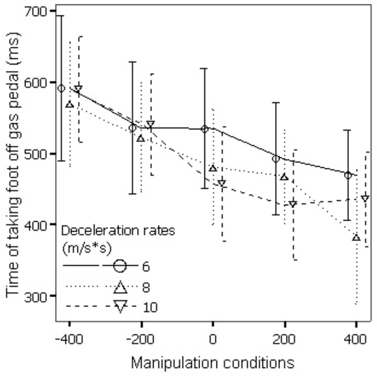

Figure 2. Time of taking foot off gas pedal (in ms) (In this and subsequent graphs, error bars represent 95% confidence intervals.)

Time of First Pressing Brake Pedal (TPB)

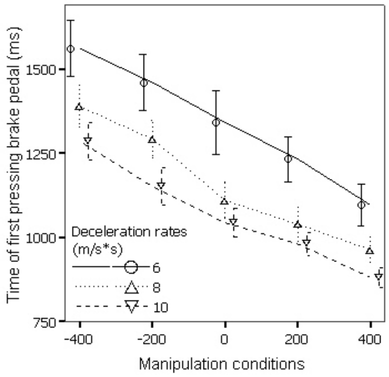

Figure 3. Time of first pressing brake pedal (in ms)

As shown in Figure 3, subjects pressed the brake pedal earlier on expansion events (+200, +400 ms) and later on contraction events (-200, -400 ms), to an extent corresponding to the manipulation levels, relative to no manipulation events (0 ms). A two-way within-subjects ANOVA confirmed a significant effect of ΔT (F(4,116)=129, p<0.001) and a significant effect of deceleration rate (F(2,118)=80.2, p<0.001), with no significant interaction (F(8,112)=1.5, p=0.162).

Time of Maximum Braking Force (TMB) and Maximum Braking Force (MBF)

As shown in Figures 4 and 5, a general trend is very obvious: subjects pressed the brake pedal to a smaller maximum force earlier for expansion events (+200, +400) and to a larger maximum force later on contraction events (-200, -400), to an extent corresponding to the manipulation levels relative to no manipulation events (0 ms). This suggests that commencing braking earlier for the expansion events left a bigger margin of safety in terms of reducing maximum braking force (i.e. less emergency braking). Alternatively, later braking was followed by harder braking, which is potentially more dangerous.

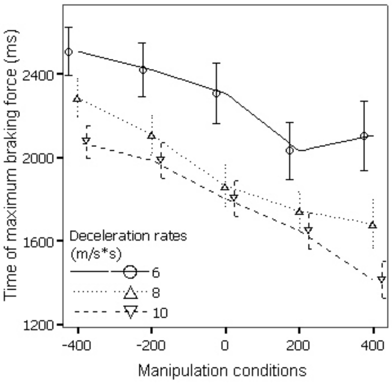

Figure 4. Time of maximum braking force (in ms)

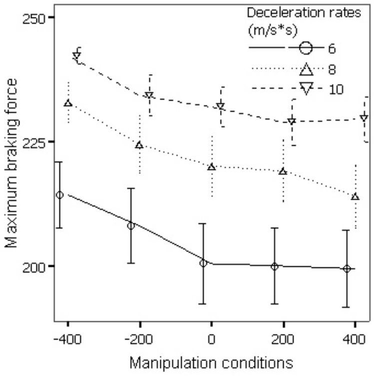

Figure 5. Maximum braking force (range is between 0-245)

Quantitatively, a two-way within-subjects ANOVA confirmed a significant effect of ΔT (F(4,116)=50.7, p<0.001) for TMB and a significant effect of deceleration rate (F(2,118)=83.4, p<0.001), with no significant interaction (F(8,112)=2.1, p=0.044). Similarly, a second two-way within-subjects ANOVA showed a significant effect of ΔT for MBF (F(4,116)=23, p<0.001) and a significant effect of deceleration rate (F(2,118)=109.9, p<0.001), with no significant interaction (F(8,112)=0.8, p=0.593).

Maximum Relative Velocity (MRV), Minimum Following Distance (MFD) and Minimum Time-to-collision (TTC)

Since both the subject controlled following vehicle (FV) and the computer controlled lead vehicle (LV) were always driving at effectively the same speed when the LV started its braking, maximum relative velocity (MRV) and minimum following distance (MFD) during braking are also important indices of braking behaviour. Basically, if subjects braked sooner, the maximum velocity difference should be smaller (ideally RV=0), minimum following distance should be greater, and therefore the margin of safety larger. The converse should hold for later braking. This is exactly what was observed in our data, whose details are not presented here due to space limitations.

The final continuous performance parameter is minimum time-to-collision (TTC), which shows the potential imminence of a collision. One advantage of this measure is that it gives us a more integrated understanding of braking behaviour, since it combines both distance and velocity information. As shown in Figure 6, subjects achieved longer minimum TTC during braking on expansion events (200, 400) and shorter minimum TTC on contraction events (-200, -400), to an extent corresponding to the manipulation levels, relative to the no manipulation events (0 ms). A two-way within-subject ANOVA showed a significant effect of ΔT (F(4,116)=133.2, p<0.001) and a significant effect of deceleration rate (F(2,118)=188.4, p<0.001), with a significant interaction (F(8,112)=4.6, p<0.001). Three separate one-way within-subject ANOVAs were then conducted for the three deceleration rates, showing a significant effect of ΔT for each of the three rates ($6m/s^2$: F(4,116)=16.4, p<0.001; $8m/s^2$: F(4,116)=62.6, p<0.001; $10m/s^2$: F(4,116)=113.3, p<0.001), with larger deceleration rates augmenting the effect of manipulation. This finding makes sense, since the same imposed TTC shift due to the ΔT manipulation should have less of an influence relative to the larger actual TTC produced by a more slowly decelerating LV.

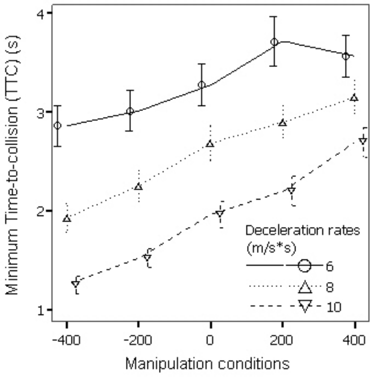

Figure 6. Minimum Time-to-collision (TTC) (in seconds)

Numbers of Rear-end Collisions and Excessive Braking

Of the1800 *fast* braking events (6, 8, $10m/s^2$) in this experiment, rear-end collision occurred 18 times (1% of the total). Of these, 11 (61% of collisions) occurred during the contraction events and 4 (22%) during expansion events. This result also supports the effect of manipulating the optical looming cue. Of the 1200 *slow* braking events (2, $4m/s^2$), 'excessive braking' took place 35 times (3%) distributed over all manipulation conditions, even though more excessive braking was expected for expansion events. This could be because the very small RV(t) values produced effective virtual displacements ($D(t) = RV(t)*\Delta T$) which were visually below the perceptual threshold.

Questionnaire

At the end of experiment, the subjects were asked, "Did the LV image appear normal during braking?". All twenty subjects said that it did appear normal to them. They were then explicitly asked, "Were you aware that the size of the LV image was manipulated, by expanding or contracting during the lead vehicle's braking in some of the braking events?". Sixteen of the 20 subjects said that they had not noticed anything; however 4 of the subjects said that they might have noticed some strange aspects of the manipulation, with comments such as: "I found the size of the LV changed rapidly during the late stage of braking, when it was closing in on my own vehicle sometimes"; or "The LV appeared closer/bigger while referring to the side post distances in some cases". These extreme situations could occur during either expansion or contraction events according to the scaling algorithm. Moreover, 2 of the 4 subjects mentioned that they even adopted a strategy to compensate for the anomalous cues from the LV image size: comparing the position of the wheels of the LV relative to the side of the road.

Another important question concerns the strategies used to respond to the braking of the LV. Many subjects indicated that they used the following cues: expansion of the taillights, expansion of the size of the LV; contraction of the visible roadway between the LV and the FV; position of the wheel on the road relative to roadside, speed of LV passing the posts along the roadside; and speed of LV passing the dashed centre lines.

Although other cues exist in this driving simulator and were indicated to have been used by the subjects, the strong results from the dependent variables suggest that braking behaviour was dependent mainly on the relative expansion rate of the size of the LV which was manipulated. In particular, for the two subjects who detected the size manipulation and avoided using size expansion of the LV, their data still show that their braking behaviour was geared directly to the manipulated optical looming of the visual image of the LV.

DISCUSSION

The results reported here generally support our hypothesis: *subjects brake sooner, or later, to an extent corresponding to the magnitude of manipulation while viewing a LV which is artificially expanding, or contracting, at a rate compatible with its being closer to, or further away from, the FV in terms of imposed TTC time shift.* This effect is best shown by the minimum TTC in Figure 6. On the one hand, minimum TTC is shifted by at least 200ms across manipulation levels, corresponding to the level of effective virtual time shift. On the other hand, the differences in minimum TTC between manipulation levels are larger than the imposed EVTS (ΔT) values, especially for contraction events. In particular, for $\Delta T=\pm 200$ms, the actual shift in minimum TTC is ±200-400ms; for $\Delta T=\pm 400$ms, the actual shift in minimum TTC is ±400-700ms. This suggests that other factors were also playing a role in controlling braking behaviour. Nevertheless, given the pattern of response, it is highly likely that information about TTC imposed through the optical looming manipulations made a significant contribution to the control of braking in this task. Whenever the size of the LV was expanded or contracted, the naturally occurring looming of the LV retinal image was amplified or reduced, such that the LV must have seemed closer to or further away from the FD, which thus caused subjects to speed up or delay their responses to the braking of the LV.

As for the choice of magnitude of EVTS manipulation (ΔT), 4 subjects did detect that "something strange" had happened during the actual experiment and 2 of them even found the size expansion of the LV image to be an unreliable cue. This did not necessarily mean, however, that those subjects actually consciously detected the online manipulation of the size of the LV. In fact, it was apparent from their remarks that they considered this rather as a technical problem with the simulator.

Although further research is needed to generalise our findings beyond the current low fidelity simulation, our results have shown that it is possible to successfully reduce or increase FD response times to a braking LV (especially a rapidly braking LV) in a controllable way. This finding has potential applications for actual driving, by manipulating optical looming cues in order to reduce rear-end collisions. An investigation of this concept is reported in Li and Milgram (2005).

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