Influence of Edge Rate, Global Optical Flow Rate, Angle, and Expansion Rate on Braking Behavior

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INFLUENCE OF EDGE RATE, GLOBAL OPTICAL FLOW RATE, ANGLE, AND EXPANSION RATE ON BRAKING BEHAVIOR

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

By

SHELDON M RUSSELL

B.S. Wright State University, 2004

2010

Wright State University
WRIGHT STATE UNIVERSITY

SCHOOL of GRADUATE STUDIES

July 17, 2010

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Sheldon M Russell ENTITLED Influence of Edge Rate, Global Optical Flow Rate, Angle, and Expansion Rate on Braking Behavior BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

Russell, Sheldon M. M.S., Department of Psychology, Wright State University, 2010. Influence of Edge Rate, Global Optical Flow Rate, Angle, and Expansion Rate on Braking Behavior

A driving simulator was used to understand the way humans control collisions. Based on the research of Smith et al. (2001), and McKenna (2004), this study altered distance to and size of a target to determine if optical angle and expansion rate were used independently to control behavior in a collision event rather than combined into a single variable, tau, as suggested by Lee (1976). Furthermore, edge rate as defined by Denton (1980) and global optical flow rate (GOFR) (Warren, 1982) were considered as possible visual sources of egomotion information. Similar to the results found by McKenna (2004), participants appeared to use bang-bang control in controlling the simulated automobile (full acceleration followed by full braking). Data also suggests that participants utilize angle and expansion rate as independent sources of information. Manipulation of GOFR and edge rate information did not influence performance in this simulation. Possibilities for future research are discussed.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>Optical Information: Time to Collision</td>
<td>3</td>
</tr>
<tr>
<td>Optical Information: Absolute Speed</td>
<td>6</td>
</tr>
<tr>
<td>Experimental Research: Collision Judgments</td>
<td>8</td>
</tr>
<tr>
<td>Hypotheses</td>
<td>12</td>
</tr>
<tr>
<td>II. METHOD</td>
<td>15</td>
</tr>
<tr>
<td>Participants</td>
<td>15</td>
</tr>
<tr>
<td>Apparatus</td>
<td>15</td>
</tr>
<tr>
<td>Display</td>
<td>16</td>
</tr>
<tr>
<td>Procedure</td>
<td>17</td>
</tr>
<tr>
<td>Design</td>
<td>18</td>
</tr>
<tr>
<td>Dependent Measures</td>
<td>19</td>
</tr>
<tr>
<td>III. RESULTS</td>
<td>21</td>
</tr>
<tr>
<td>Driving Behavior</td>
<td>21</td>
</tr>
<tr>
<td>Optical Features</td>
<td>22</td>
</tr>
</tbody>
</table>

iv
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Diagram of state variables for one vehicle</td>
</tr>
<tr>
<td>2.</td>
<td>Diagram of state variables for two vehicles</td>
</tr>
<tr>
<td>3.</td>
<td>Graph of expansion rate, tau, linear combination and angle strategies</td>
</tr>
<tr>
<td>4.</td>
<td>Field of safe travel</td>
</tr>
<tr>
<td>5.</td>
<td>Sample displays from the four optical conditions</td>
</tr>
<tr>
<td>6.</td>
<td>Sample time history from one participant for a 200m starting distance</td>
</tr>
<tr>
<td>7.</td>
<td>Peak velocity in the learning phase</td>
</tr>
<tr>
<td>8.</td>
<td>Peak velocity in the transfer phase</td>
</tr>
<tr>
<td>9.</td>
<td>Final stopping distance</td>
</tr>
<tr>
<td>10.</td>
<td>Accelerator release, learning phase</td>
</tr>
<tr>
<td>11.</td>
<td>Accelerator release, transfer phase</td>
</tr>
<tr>
<td>12.</td>
<td>Initiation of braking, learning phase</td>
</tr>
<tr>
<td>13.</td>
<td>Initiation of braking, transfer phase</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Properties of optical criteria</td>
<td>43</td>
</tr>
<tr>
<td>2. Overall design</td>
<td>44</td>
</tr>
<tr>
<td>3. Optical R squared, intercept, slope, and strategy for release of the accelerator</td>
<td>45</td>
</tr>
<tr>
<td>4. Optical R squared, intercept, slope, and strategy for initiation of braking</td>
<td>46</td>
</tr>
<tr>
<td>5. Proportion of participants optical strategies for the learning and transfer phases</td>
<td>54</td>
</tr>
</tbody>
</table>
Introduction

A fundamental task performed many times by many people each day is making a safe stop while driving. Whether stopping behind another vehicle, a stop sign, or a crossing pedestrian the fundamental task is the same: Decelerate to a stop in front of the object (or intersection) so as the driver does not injure himself/herself, or others. Furthermore, stopping safely also involves controlling deceleration such that it is does not occur too quickly, or too slowly. Slamming on the brakes and decelerating too quickly may cause an accident as trailing drivers do not react in time (not to mention being uncomfortable for the driver and passengers alike), while decelerating too slowly (assuming a collision is still avoided) may disrupt traffic and cause unnecessary delays. The question, then, is how do human drivers gain the information that they need to successfully perform this task in a routine manner.

There is little argument that driving is a visual task. Successfully avoiding collisions and making safe stops, along with navigating twists and turns in the road, requires that the driver be alert in observing his or her surroundings. Fitting with these conclusions, driving has been categorized as a visually guided action by Fajen (2005). Visually guided actions are those that require precise, continuous visual feedback in order to perform the task successfully.

Certainly there is consensus among researchers that visual feedback is important for driving, but why is it that visual information is so much more valuable than input from other sensory modalities? The answer lies in the physical constraints of driving. Specifically, driving involves the operation of an inertial system bound by the laws of physics. Physical laws of inertia require that the driver have prospective knowledge of
the state of the vehicle’s future position and velocity relative to their inputs that take place in the immediate present, as well as knowledge of the layout of the environment. For humans, the visual system is the only sensory system available that can successfully provide this prospective information about the state of the system. The types of state information available will vary depending on the specific situation that is encountered. In the case of collision avoidance, differences in the available information sources occur depending on whether or not the object encountered is stationary, or if the object encountered is moving.

In the simplest situation of collision avoidance while driving, a vehicle is traveling in a given direction at a constant speed, traveling towards a stationary object, such as a parking barrier or wall (see Figure 1). In the case of a stationary object the minimum number of state variables needed to successfully avoid collision two: The absolute velocity of the vehicle as well as position information relative to the object. Assuming a constant direction, the physical constraints set forth a specified time to collision with the object based on the current position and velocity, as seen in Equation 1,

\[ \frac{P_1}{V_2} = \text{TTC}, \]

where \( P_1 \) is position (in terms of distance to the object), and \( V_2 \) is velocity, and \( \text{TTC} \) is the instantaneous time to collision.

The second situation to be considered involves a moving object such as another vehicle, as in Figure 2. In the two vehicle scenario (still assuming direction is held constant), three variables are now required. Each vehicle still has an absolute velocity that is independent of the other, but there is also a relative difference in velocity between the two vehicles, as shown in Equation 2,
\[ v_1 - v_2 = r_v, \]  

(2)

In this example, \( v_1 \) is the absolute velocity of vehicle 1 and \( v_2 \) is the absolute velocity of vehicle 2, and \( r_v \) is the relative velocity between the two vehicles.

Also, while not a new variable, the position of, or separation between, the two vehicles becomes more dynamic than in the stationary object case, as relative velocity differences lead to dynamic changes in the relative position between the two vehicles. Relative position information can be computed by Equation 3,

\[ p_1 - p_2 = r_d, \]  

(3)

where \( p_1 \) is the position of vehicle 1, \( p_2 \) is the position of vehicle 2, and \( r_d \) is the relative distance between the vehicles. Time to contact information can be computed by using the relative position and velocity values, rather than absolute values of velocity.

Based on the knowledge of the physical constraints of driving, a good mapping of visual information to state information is required. The previous examples demonstrate that at least three variables would need to be specified optically: Absolute velocity of the first vehicle, relative velocity, and position information. A fourth variable, time to contact, could also be specified directly using these visual features, as demonstrated in Equation 1.

**Optical Information: Time to collision**

For individual objects, the necessary optical variables for judgments about speed and distance relative to the observer would be optical angle, and the rate of angular change (expansion rate). The optical angle of the object specifies the relative position of an object as a function of distance and the size of the object. The angular rate (or expansion rate) specifies the relative speed of the object as it moves through the visual.
field. Angular rate would relate to speed as a function of the distance away from an object, the size of the object, and the relative speed of the object and the observer.

Research has been conducted to determine relationships of angle and angular rate that are specific to collision. This specification can be referred to as time to contact (TTC). Lee (1976) proposed that time to contact judgments could be based on the optical invariant tau (τ) which is equal to the inverse of the rate of dilation of the retinal image of an object. Therefore, the optical variable τ is defined as the ratio of optical angle and expansion rate as follows:

$$\tau = \frac{\theta}{\theta'}$$

(4)

where θ is the instantaneous optical angle of an object and θ’ is the expansion rate of the same object.

Although tau is often considered the variable that specifies time to collision, Lee also proposed that the rate of change in the value of tau (the time derivative), tau-dot, is required for control of deceleration since tau alone is an instantaneous time to collision. Tau-dot can be used for continuous control of deceleration such that when tau-dot has a value of -.5 it will bring an observer to a rest exactly at the target. Increases in the value of tau-dot (i.e. >-.5) will cause a stop before the target, while decreases in tau-dot (i.e. <-.5) will cause a stop beyond the target, and therefore generate a collision. Given that it is typically desirable to avoid collisions while in a vehicle, a tau-dot strategy will likely be slightly higher than -.5 in order to create a margin of safety (Lee, 1976).

Despite widespread acceptance, questions have arisen from Lee’s formula for time to contact. Reviews of the experimental research on tau by Tresilian (1999) and Wann (1996) indicate that there are issues with tau being the sole specification for TTC.
Wann (1996) concludes that although a tau theory has some explanative power, there is a lack of evidence for its use in natural settings. Tresilian (1999) also indicates that tau hypotheses only hold under strict psychometric studies in which tau is the only information available to participants, and that in real world settings multiple sources of TTC information are available. Both reviews also agree that TTC judgments can be situation dependent, can be biased by object size, and can be biased by object irregularities. These factors point to the idea that tau theories can approximate a more complex interplay of optical sources containing collision information.

A series of experiments by DeLucia and Warren (1994) indicate a significant effect of object size on decisions of when to “jump” to avoid a collision. Given that tau is a ratio of an object’s angular size to its expansion rate, size differences should not create differences in collision avoidance judgments if individuals are using tau as the sole indication of TTC. Throughout the series of experiments, participants were viewing an ego-motion display, moving towards an object and had the ability to initiate a jump over that object. Observers responded later to smaller objects, and earlier to larger objects. The effect of object size indicates that angular size information may be independent of expansion rate information.

Additional research has also supported the idea that tau may not be a single property of the visual field (Smith, Flach, Dittman, & Stanard, 2001). In a simulated ball hitting task, Smith et al. found that optical angle and expansion rate were each independent sources of information, and not confined to a ratio. In this study, the participants’ task was to swing a pendulum at the correct moment to initiate a hit with an oncoming ball. Both ball size and ball speed were manipulated. The results showed an
effect of both ball size and ball speed such that in early trials participants were systematically responding too early to slower and larger balls. This strategy is consistent with an expansion rate alone strategy (participants were releasing the pendulum based on a specific expansion rate and ignoring angle information). As participants gained more practice, information for both angle and expansion rate appeared to be utilized. This research suggests that optical angle and expansion rate are two separate degrees of freedom that are coupled together not as a ratio, but in the form of an additive function that can be tuned to the constraints of a particular task.

**Optical Information: Absolute Speed**

In addition to object motion, egomotion, or self-motion, can be specified by visual features. Egomotion information can provide a way to judge the absolute speed of the observer, independent of objects in the visual field. Two features of the visual field that have been observed to have effects on self-motion judgments are global optical flow rate (GOFR), and edge rate.

Gibson (1938) theorized that a field of safe travel was created as individuals move through the environment. According to Gibson, this flow field gives individuals much of the necessary information to navigate safely through their environment. Subsequent research by Gibson, Olum, and Rosenblatt (1955) in the context of flight, and Gibson (1958) in the context of land based navigation, further theorized that this field of safe travel was specified as an optical flow field. This flow field can reveal the constraints on action within the world, and these constraints specify the field of safe travel through the environment. Components of this flow field important for detection of speed and distance include optical angle, angular expansion rate, and global optical flow rate.
Warren (1982) measured specific properties of the flow field, and used the term global optical flow rate (GOFR) to describe the observed phenomenon. GOFR is defined by the ratio of height of the observer to the speed of the observer, as seen in Equation 5,

\[
\text{GOFR} = \frac{V}{H},
\]

where \( V \) is the velocity of an individual, and \( H \) is the height of the individual, typically measured in eyeheight.

Given this relationship, when height is constant GOFR is proportional to changes in speed, and vice versa. In the context of driving, altitude is typically unchanging, which means GOFR can reliably specify absolute speed. As GOFR is a global measure, averaging the motion around a focus of expansion, in a simulated display it will be independent of texture density.

Another possible source of self-motion information is edge rate, as defined by Denton (1980). Edge rate is the number of discontinuities that pass by a fixed point in the visual field. In the context of driving, these discontinuities could be lane divider lines on a roadway, telephone poles, or guardrails. In a simulator setting, edge rate would be a function of both the texture density and absolute speed of the observer, such that increasing speed will increase edge rate, as will increasing the density of the texture elements passing by the observer (Denton, 1980).

Using a driving simulator, Denton (1980) found participants decelerated at a faster rate and to slower speeds when line spacing was lawfully decreased, such that the lines on the simulated roadway were moved closer together as the participant was moving past them. Furthermore, Denton applied this finding to an actual roadway and found that gradually decreasing the space between lines on an actual roadway in a similar fashion
caused drivers to slow down when compared to control sections of roadway.

Research has furthered understanding of the influence of GOFR and edge rate on perception of self motion (Larish & Flach, 1990; Dyre, 1997). With both of these features of the visual field as different sources of information for absolute speed, research has been done to determine the relative influence of each. Research that includes both edge rate and GOFR finds that there is some combination of both that leads to the perception of the speed of self motion. The overall influence of each seems to depend somewhat on the type of task used to test the relationship. For example, research done by Dyre (1997) on optic flow and edge rate suggests that flow rate is the dominant cue for participants to judge whether or not they are moving, while research done by Larish and Flach (1990) suggests an edge rate strategy is dominant in judgments about how fast one is actually moving.

**Experimental Research: Collision Judgments**

Research attempting to uncover the roles of edge rate and GOFR in the context of driving has been a focus of study by Fajen (2005). In a braking task, Fajen manipulated edge rate and GOFR by adjusting the eyeheight of the participant as well as varying the texture density of the ground plane. Participants in this study were in control of a brake, and were responsible for avoiding a collision with an oncoming object that was being approached at a fixed rate.

The results from this study indicate a statistically significant stronger influence of GOFR over edge rate on the braking behavior of participants. These effects were such that when moved to a lower eyeheight (increasing the GOFR), the final stopping distance from the target was greater. Raising the eyeheight (decreasing the GOFR) led to the
opposite effect: Stops were closer to the target and therefore more collisions were observed. Edge rate effects were similar but less effective, in that increasing edge rate led to slightly larger stopping distances and decreasing edge rate led to slightly closer stops and more collisions.

McKenna (2004) also studied automobile braking using a desktop computer simulator. The task was modeled in such a way as to further understand the optical variables involved in the control of collisions while driving, rather than to study driving per se. Specifically, McKenna’s study focused on further understanding the relationship of tau with braking behaviors, as well as understanding control strategies used by participants.

The simulator used by McKenna was designed to represent driving on a normal two-lane road and stopping in front of a wall. The simulated vehicle was modeled on a Corvette, with the participants’ viewpoint as that of the driver. The task for each participant was to pull up to a target and stop “at a comfortable distance” from the wall. Participants were given no instruction as to how to do the task (i.e., there were no traffic laws or other similar rules) and participants could accelerate and brake in any fashion they wished. The independent variables manipulated were size of the target (5 levels), starting distance from the target (5 levels), and braking dynamics (3 levels).

These independent variables were manipulated in such a way as to observe which optical features caused a change in participants’ braking and accelerating responses. The complete time histories for each trial were recorded. The time history included location relative to the target, accelerator activity, braking activity, and speed. The two dependent variables were the release of the accelerator and initiation of braking.
When operating the simulator, participants appeared to use a non-proportional, bang-bang style of control where maximum acceleration was used followed by maximum braking. The changes in brake dynamics did not seem to generate any change in participants’ control style, as participants utilized a bang-bang strategy regardless of manipulations of braking dynamics.

In addition to the time history data, McKenna converted the real time performance data into an optical history (optical domain). Analyzing driving performance data in the optical domain allowed for a deeper understanding of relationships between the optical angle and expansion rate used to calculate tau. When a linear regression was created for the angle and expansion rate at a critical event(s) (for McKenna these events were the release of the accelerator and the initiation of braking) the different properties of slopes and intercepts of the resulting equations can indicate which optical criterion was dominant for that particular event. The criterion considered are as follows: Angle, expansion rate, tau, and linear combination of angle and angular rate. A list of these criterion as well as associated properties of slope, intercept, and degrees of freedom can be seen in Table 1, and a graph including examples of angle, expansion rate, and tau is included in Figure 3.

Examination of the slope, intercept, and variance accounted for each regression line revealed which particular strategy is being utilized. In the case of expansion rate, the line would be nearly parallel with the x-axis and would have a non-significant slope but a significant intercept. Participants using this strategy would be responding to a critical expansion rate alone, and not utilize information provided by visual angle. Tau strategies would have significant slopes, with a non-significant zero intercept, since participants
would be responding to a constant time-to-contact regardless of the size of the object and speed of approach. A linear combination strategy, such as what was observed in Smith et al. (2001), would have both a significant slope and significant intercept. In this case responses would be based on a critical value of the combination of angle and expansion rate. Lastly, an angle alone strategy would always have a non-significant slope. The intercept in an angle-alone strategy could be either significant, or not significant. Angle-alone strategies would produce lines perpendicular to the x-axis.

A particularly interesting finding by McKenna (2004) was that after practice operating the simulator, the data approximated a tau function. However, an overlay of the vehicle dynamics showed that participants seemed to be operating at the very edges of the simulator dynamics (achieving maximum acceleration and initiating full braking). This leads to a difficulty in determining whether participants were responding to tau, or were simply adapting to the dynamics of a system that has constraints consistent with tau. However, when looking at the dynamic boundary of the last possible time to brake safely and the tau ratio plotted in the same space, we can see that a tau strategy meets the requirements of braking safely, because if participants respond to tau, they will be on the “safe” side of the maximum braking curve (Figure 4). Therefore, participants were likely adapting to the constraints of a system to which a linear combination strategy resembling tau was an effective solution.

To summarize, the line of research from Smith et al. (2001), Stanard et al. (2004), and McKenna (2004) suggests that participants settle on a two degree of freedom solution (angle and expansion rate as independent sources of information) rather than a single degree of freedom solution (tau) for humans controlling collisions. Although this fits
with the inertial constraints associated with control of collisions, (angle containing position information and expansion rate containing velocity information) there may be other visual sources of velocity information (GOFR and edge rate) that are also important for the control of collisions. Based on these theoretical ideas, the next logical step in research following McKenna (2004) will utilize a change in the display properties to address some of the remaining questions from McKenna, as well as expand on ideas from Fajen (2005). Modifications to the simulator used by McKenna involved manipulations of eyeheight of the participant to change GOFR, as well as manipulating ground texture to alter edge rate information.

**Hypotheses**

If GOFR is an important source of information about absolute speed while driving, creating a condition in which the participant transferred to a viewing condition closer to the ground should create a percept of increased speed when compared to the original eyeheight. The inverse should also be true, so that participants given a higher viewing condition should have a percept of decreased speed. These manipulations are likely to have an effect on braking behavior as GOFR was shown to have an effect on initiation of braking and stopping distance by Fajen (2005). Another important optical source of information for determining speed is edge rate would also be useful. Given that edge rate is a function of texture density, changing a textured ground plane to a single solid color should produce a change in braking behavior if edge rate is providing additional information about absolute speed.

Furthermore, McKenna’s (2004) results suggest that some participants would be operating the vehicle outside the boundaries for successful completion of the task if the
target was at a closer starting distance. To determine if observers operate the simulated vehicle differently based on starting distances, (in the present study) starting distance from the target was varied such that one of the starting distances will be nearer, two will be identical, and two will be further than those used by McKenna (2004).

The hypotheses for the present experiment are as follows:

H1: Participants will utilize a bang-bang (full acceleration followed by full braking) strategy of control to complete the task.

H2: Transferring to different optical conditions will cause differences in measures of general driving behavior in the following ways:

H2a: When transferred to a lowered eyeheight, participants will stop further from the target, generate fewer crashes and reach lower peak velocities.

H2b: When transferred to a raised eyeheight condition, participants will stop closer to the target, generate more crashes and reach higher peak velocities.

H2c: When transferred to a condition with all texture elements removed, participants will alter their driving behavior, although changes could be made in either direction (i.e. participants could use a more cautious strategy generating lower speeds and lower collisions, or adopt a more reckless strategy, indicated by higher speeds and more crashes)
H3: Transferring from learned optical conditions to one with different optical conditions will result in participants responding to different combinations of angle and expansion rate.
Method

Participants

Twenty observers participated in this study, with ages ranging from 18 to 24 years. Participants were university students who received course credit for participation. Four participants were excluded from analysis due to failure to complete the experiment. Data from sixteen participants were included in the final analysis. All participants had normal or normal to corrected vision. All participants were licensed drivers.

Apparatus

The simulation was designed in LynX Prime (Ver 1.2) and run on an Alienware (Miami, FL) PC workstation. Individual elements placed in the simulator were made in Creator (Ver 2.6), including the ground and road surfaces, as well as the target. Both LynX Prime and Creator are software products of Multigen-Paradigm. The simulator was shown through a Sony 18” monitor with a refresh rate of 42 Hz. Resolution of the display was set to 1280 by 1024 pixels. The simulator program was set to collect data at a refresh rate that matched the display (i.e. data was collected 42 times per second). The optical size of the display was set to 14.5 degrees of visual angle horizontally. An oval cut-out (10” high, 13 ½” across) from black poster board was placed over the monitor so that the participant could not see the edges of the monitor. The experiment was conducted in a small windowless room painted black. The room was illuminated by incandescent light.

A Logitech Formula Force GP driving system (including an accelerator and a brake pedal) was used by the observer to initiate changes in velocity. The device was set up to be similar to an automobile, so that displacement of the right pedal would
cause the vehicle to accelerate, while pushing the left pedal would cause the vehicle to decelerate. The participants were allowed to adjust the position of the pedals to a comfortable position. Since the participants had no control over steering, the steering column was placed out of reach from the participant.

Display

The layout of the display was designed to resemble a two-lane road. The observer was placed in the right lane of the road to simulate natural (North American) driving conditions. Ahead in the right lane was the target. The target was a large square, colored orange with white texture, which again was created in the same manner as the road and ground patterns. The bottom of the target was placed slightly above the road (0.02 m above the ground plane). The position of the target was shifted for the various target sizes so that it was always centered in the right lane (Figure 5 depicts the starting conditions of the display in the four optical conditions).

The ground pattern was created using two shades of green, and was formatted using the fractal texture pattern in Creator. The road texture was created in a similar manner to the ground, using two shades of gray in the pattern. The road texture was integrated into the ground texture, in order to minimize aliasing during optical manipulations of eyeheight. The width of the road was 7.31 m (24 ft) and the distance was such that neither the end nor the beginning of the road was visible to the participant. The road and all its markings (with the exception of the left border lane line, see below) were designed in keeping with regulations from the Ohio Department of Transportation (2008).

Drawn into the road texture were yellow lane dividers, placed in the center of the
road, and white border lane lines, placed to appear approximately 6 in. from the edge of
the road on each side and continuing on ad infinitum. Markings were integrated within
the road texture to minimize aliasing. The center lines (indicating a two lane highway,
with passing permissible) were 3m long (10 ft) and were separated by 9 m (30 ft). This
creates a cycle of 12 m. The number of center lines in a trial varied based on the distance
to the target. The shorter the distance to the target, the fewer the center lines the
participant would pass. The widths of the center lines and right border marking were 0.1
m. The width of the left lane line was twice as large as the right lane line to minimize
aliasing.

The car was programmed to have capabilities similar to that of a Corvette. Control
dynamics for the vehicle came from a web page entitled *Car Physics for Games.*
(Monster, 2003)

**Procedure**

Using the desktop computer simulation, participants were instructed to
pull up and stop at “a comfortable distance” from the wall on the computer screen.
Participants completed the trials at their own pace. When the end of each trial was
reached (either by a successful stop or by a collision with the wall) the participant pressed
the spacebar to move on to the next trial.

There were 2 phases of the experiment. The first phase of the experiment
(learning phase) consisted of 10 blocks of trials and took approximately 90 minutes to
complete. Each block was a randomized combination of all 5 target sizes and all 5
starting distances, totaling 25 trials per block and 250 trials for the learning phase. Phase
3 (transfer phase) consisted of 10 blocks of trials (each block being 25 trials, for a total of
275 trials) and also took approximately 90 minutes to complete. The two phases of the
experiment were completed on the same day, and were separated by a break of at least 90 minutes. After returning from a 90 minute break, participants completed 1 block (25 trials) of visual features that were identical to the learning phase. This was to reinforce the already learned optical features before being transferred to new optical features.

All participants received the same stimuli for the learning phase. After completion of the learning phase, and subsequent refresh block of trials, there were four different sets of 10 blocks of trials. Participants experienced a different view of the task based on the manipulation of the optical variables of eyeheight (raised or lowered) and texture information, expected to have an effect on the braking behavior.

**Design**

The experiment utilized a 4 x 2 x 5 x 5 mixed design with four optical transfer conditions as a between subjects factor, two levels of phase (learning versus transfer) as a within subjects factor, five levels of target size as a within subjects factor, and five levels of starting distance as a within subjects factor. The five target widths presented by McKenna of 1, 2, 3, 4, and 5 m were used, with the height of each target set to double the eyeheight of the observer. The five initial starting distances were set to 50, 100, 200, 400, and 800 m.

There were four optical transfer conditions. Condition one served as a control and no change in the task was introduced. Condition two introduced a change in eyeheight, which was set at .5 times the height used in the learning phase. The ground texture pattern remained unchanged. Condition three introduced a different change in eyeheight, increasing to double the eyeheight in the learning phase, again with no change to ground texture. Condition four had all of the ground texture elements removed from the task,
with the eyeheight remaining unchanged from the learning phase. Table 2 provides a representation of the basic experimental design.

Trials in the transfer phase proceed in an identical way as in the learning phase with the addition of the optical manipulations. Target sizes (both widths and heights) and starting distances remained unchanged.

**Dependent Measures**

The analysis for this experiment included several dependent measures with the focus being comparison of the last block of learning trials with the first block of optical transfer trials. General measures of driving behavior included the number of crashes per block, final stopping distance from the target for each trial, and peak velocity of the vehicle for each trial.

Time histories including continuous control input information (accelerator and brake) and vehicle position information were recorded. Time histories indicated the points for the release of the accelerator and initiation of braking to be observed as dependent measures. The criteria for the initial release of the accelerator was identical to that used by McKenna (2004) and is as follows:

- The first reversal of the accelerator pedal displacement followed by a sustained monotonic deceleration to a point below 10% of maximum displacement.
- If this reversal was done shortly after initiation of the accelerator, and followed quickly by another initiation of the accelerator, this was deemed indicative of a readjustment of the foot on the accelerator. Therefore, these actions will not be selected as the release of the accelerator.
The criterion for the initiation of braking (McKenna, 2004) was as follows:

- The start of the first brake displacement that exceeds 10% of full braking.

Optical state space was used to analyze the relationship of optical angle and angular rate on the release of the accelerator and initiation of braking. This relationship was analyzed to determine if the effects are similar to a ratio (which would be consistent with τ) or an additive function using the significance of the slopes and intercepts as criteria, as was previously described in Table 1.
Results

Time histories recorded for each trial yielded dependent measures for both general driving behavior as well as optical measures. A sample time history can be seen in Figure 6. Time history data included peak velocity information, final stopping distance, and the event of a collision. Release of the accelerator and initiation of braking events were identified by the criteria mentioned above, and angle and expansion rate were calculated based on the velocity, target size, and distance to the target at the time of the event.

Driving Behavior

A 4x2x5x5 mixed repeated measures ANOVA, using peak velocity as a dependent measure, revealed a significant main effect of starting distance $F(4,12) = 314.4, p < .000$. Peak velocity increased as starting distance increased. No other main effects or interactions were significant for peak velocity. A graph of the peak velocities by condition can be seen in Figures 7 (learning phase) and 8 (transfer phase).

A 4x2x5x5 repeated measures ANOVA, using stopping distance as a dependent measure, revealed a significant main effect of starting distance, $F(4,12) = 6.4, p < .05$. No other main effects or interactions were significant. In the event that a trial ended in a collision (no stopping distance) the participant’s overall mean for that phase was substituted. Final stopping distance increased as starting distance increased. A graph of final stopping distance can be seen on Figure 9.

A 2x4 chi-squared analysis, with 3 degrees of freedom, for the number of crashes revealed no significant relationship between phase (two levels) and optical condition (four levels), $\chi^2 = .90 \ p > .05$. The average number of collisions for the learning phase was
15.75 with a standard deviation of 3.59, while the transfer phase had an average value of 17.25 collisions with a standard deviation of 4.27.

A second 2x4 chi-squared analysis, with 3 degrees of freedom, for the average velocity at the time of collision no significant relationship between phase (two levels) and optical condition (four levels), $\chi^2 = 1.9$ p > .05. The average velocity at the time collision for the learning phase was 19.05 m/s with a standard deviation of 19.05, while the transfer phase had an average value of 20.22 m/s at collision with a standard deviation of 13.42.

**Optical Features**

Release of the accelerator and initiation of braking events were identified for each trial as previously mentioned and angle and expansion rate of the target at the occurrence of each event was calculated based on the following equations for angle (Equation 6), and expansion rate (Equation 7):

\[
\theta = \text{ATan} \left( \frac{(\text{Target Size}/2)/\text{Distance}}{1} \right) * 180/\pi ,
\]

\[
\theta' = \frac{(\text{Target Size}/2) * \text{Velocity}}{(\text{Distance}^2+(\text{Target Size}/2)^2)} *180/\pi .
\]

Data for each phase was plotted in a scatter plot (one plot per phase for accelerator release, a second for initiation of braking, four plots total per participant), using angle as the X values and expansion rate as Y values. A best fitting line (linear regression) was fit to the data, and the slope, intercept and R squared were recorded. A second set of plots was produced for the transfer phase.

For the release of the accelerator, a series of 2x4 mixed ANOVA analyses revealed no significant differences in slope, intercept, or model fit for any of the optical conditions or between phases. Figures 10 and 11 show scatter plots for one participant’s
release of the accelerator for both learning (Figure 10) and transfer phases (Figure 11). Initiation of braking analyses also utilized a series of 2x4 mixed ANOVAs and no significant differences were observed in slope, intercept, or model fit. Initiation of braking for the same participant is plotted in Figures 12 (learning phase) and 13 (transfer phase).

Optical information at the release of the accelerator and the initiation of braking is presented in Table 3 (accelerator) and Table 4 (brake). Overall, R-squared values were high, with the lowest value for accelerator release at .748 and .736 for braking among all phases. Also noted in the table is the classification of the strategy used (tau or linear combination). Classification was evaluated by a t-test conducted as part of the calculation of the regression slope. The t-test compared the value calculated for the intercept to 0, and a significant difference from 0 is indicated on Table 3 (accelerator) and Table 4 (brake.). All tests had 24 degrees of freedom. This criterion is adopted from Stanard et al (2004). This comparison indicates that most participants’ data fit a tau strategy, although there are some data that appear to fit a linear strategy combination and some participants use different strategies in each phase. A summary of the proportions of each strategy can be seen in Table 5.

**Discussion**

Overall, the data suggest mixed results for the hypotheses tested in this experiment. The results of the analysis indicate a significant main effect of starting distance on peak velocity. As is seen in Figures 7 and 8, peak velocity increased as a function of starting distance. This is not unexpected, as participants also appeared to adopt a bang-bang strategy utilizing maximum acceleration followed by maximum braking, as was expected.
(Hypothesis 1). Utilization of a maximum acceleration strategy would lead to higher peak velocities at further distances of travel.

Although differences in general measures of driving behavior were expected to occur based on manipulations of the visual features, (Hypothesis 2a, 2b, 2c), the data do not support this Hypothesis. When observing plots of peak velocity comparing optical conditions (Figure 8), the results look remarkably similar regardless of optical condition. These results are particularly surprising for the no-texture conditions, given the expectation that absolute velocity information provided by GOFR and edge rate was expected to be important to this task.

Similar to peak velocity, a significant main effect of starting distance on final stopping distance was observed. The data indicate that participants stopped at a further distance from the target based on the initial starting distance. This finding is consistent with a speed, accuracy, and distance trade off that is expected in ballistic movements as presented by Fitts’ (1954). As part of a bang-bang strategy, participants appear to have performed the experimental task as a ballistic movement towards the target. Farther targets were approached with less accuracy, in that the stopping distance was further away and it was approached at a higher speed.

The results suggest that manipulation of optical features did not significantly impact the accelerating or braking behavior of participants. Consistent with the results for peak velocity and starting distance, the bang-bang strategy adopted by participants was similar across the different optical manipulations, in that there were no observed differences in the slopes, intercepts, or variances accounted for between phases for either the release of the accelerator or initiation of braking. Based on these data, Hypothesis 3
was not supported. Analysis of the slopes and intercepts suggest that most participants utilized a tau like strategy with a near zero intercept and a significant slope in both phases of the experiment. Although some participants’ data indicate a linear combination strategy some of the time, the results were not consistent enough to generate a difference in intercept between phases or optical conditions.

The results of this experiment do not agree with those of Fajen (2005). Fajen found that initiation of braking occurred earlier when GOFR was increased but actual velocity was the same as conditions in which GOFR was decreased (through manipulation of eyeheight, as was done in the current experiment). Although this experiment did not generate a similar finding, differences in the two experiments may be the cause. Specifically, participants in Fajen’s (2005) study began the trial moving towards a target at a constant speed (and therefore GOFR) and had active control over a brake to decelerate. In the present study, participants had control over both the acceleration and the braking of the vehicle.

It may be that active control of acceleration and braking is a task with different constraints, and therefore requires different optical information. For example, if participants are traveling towards an object at a constant speed in a simulation, they must ascertain the speed at which they are traveling completely based on optical features. When the participants gain control over the acceleration, they may gain information by manipulating the rate of acceleration, as well as reaching maximum velocity in that there is an intact perception/action loop when participants are in control of both acceleration and braking. In the present study, it appears that practice with the simulation was enough to allow participants to use one of two strategies. Either the participants quickly switched
between optical sources of information, or participants learned to ignore GOFR and edge rate information in the learning phase, and responded to angle and expansion rate exclusively thereafter. Either strategy allowed participants to continue using a bang-bang strategy regardless of the optical changes introduced in the present study.

Further analysis of the data from the present experiment may also reveal significant differences between normal viewing conditions and conditions with optical changes. Specifically, future analyses should include the very first block of trials in the learning phase as well as the very last block of trials in the transfer phase. Analysis of the first block of trials may reveal a learning pattern in showing different relationships with angle and expansion rate than those observed in the last block of learning trials. Furthermore, it may be that differences in strategy emerge over time, as participants gain more practice with the simulation. In addition, additional pulses on the brake pedal and accelerator could be analyzed to determine if there is a difference in adjustments made as a function of optical condition.

McKenna (2004) concluded that it is extremely difficult to decouple the optical information from the constraints associated with the bang-bang control strategy adopted by the participants, and the same is true in the present study. Although individuals may simply respond to tau, the tendency for participants to switch the weighting of optical parameters seems to indicate that they are tuning the weightings of angle and expansion rate based on an understanding of the dynamics of the system. It is possible that people tune to the optical parameter(s) that best match the dynamics of the task at hand, which in turn allows for an understanding of those physical constraints. In the case of an inertial system, physical constraints requires that the optical parameters match the position and
velocity relationship, which will be approximated by a strategy that resembles tau, even if the strategy utilized is a linear combination of angle and expansion rate. Future research should continue to address this relationship.


Figure 1. Diagram of state variables for one vehicle. Where P1 is the position of the vehicle and V1 is the velocity of that vehicle.
Figure 2. Diagram of state variables for two vehicles. Where $P_1$ and $V_1$ represent position (relative to the object) and velocity for vehicle 1, $P_2$ and $V_2$ are position and velocity for vehicle 2.
Figure 3. Graph of expansion rate, tau, linear combination, and angle strategies. The data presented are hypothetical, to demonstrate the relationship of angle and expansion rate in optical space.
Figure 4. Field of safe travel. Graph taken from McKenna (2004) for participant 1 on block 25, with a dashed line added to approximate a tau function. Filled shapes represent release of the accelerator, while open shapes represent initiation of braking. Each of the maximum acceleration curves (solid lines) represents the maximum acceleration that is possible at each starting distance. The maximum braking curve (dotted line) represents the maximum deceleration of the vehicle: Braking after this point will always result in a collision. The safe field of travel and areas of inevitable collision are indicated as well. In this system a tau-like strategy allows for initiation of braking before exceeding the limits of the brake.
Figure 5. Sample displays from the four optical conditions. The control condition is depicted in A, eyeheight lowered in B, eyeheight raised in C, and the no texture condition is displayed in D.
Figure 6. A sample time history from one participant for a 200 m starting distance. This time history clearly displays a bang-bang strategy of one maximum acceleration action followed directly by initiation of full braking. The solid black line represents activity on the pedals: Any positive represent pressing of the accelerator, while negative values represent braking. The dotted line represents position, such that the participant starts at 0 m and travels towards the target 200 m away. The dashed line represents velocity during the trial.
Figure 7. Peak velocity in the learning phase. Peak velocity values for the learning phases as a function of initial starting distance and optical condition.
Figure 8. Peak velocity in the transfer phase. Peak velocity as a function of initial starting distance as well as optical condition for the transfer phase.
Figure 9. Final stopping distance. Final stopping distance for the learning and transfer phases as a function of initial starting distance. Error bars represent ± 1 standard error.
Figure 10. Accelerator release, learning phase. Scatter plot for the release of the accelerator from one participant in the learning phase. Y axis values represent expansion rate, while X axis values correspond to angle. The equation for the best fitting line is displayed, indicating the slope intercept and R squared value.
Figure 11. Accelerator release, transfer phase. Scatter plot for the release of the accelerator from one participant in the transfer phase. Y axis values represent expansion rate, while X axis values correspond to angle. The equation for the best fitting line is displayed, indicating the slope intercept and R squared value.
Figure 12. Initiation of braking, learning phase. Scatter plot for the initiation of braking from one participant in the learning phase. Y axis values represent expansion rate, while X axis values correspond to angle. The equation for the best fitting line is displayed, indicating the slope intercept and $R^2$ squared value.
Figure 13. Initiation of braking, transfer phase. Scatter plot for initiation of braking for one participant in the transfer phase. Y axis values represent expansion rate, while X axis values correspond to angle. The equation for the best fitting line is displayed, indicating the slope intercept and R squared value.
Table 1.

*Properties of optical criteria*

<table>
<thead>
<tr>
<th>Optical Criterion</th>
<th>Degrees of Freedom</th>
<th>Slope</th>
<th>Intercept</th>
<th>$R^2$</th>
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<td>Angle</td>
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<td>N.S. or large</td>
<td>N.S.</td>
</tr>
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<td>Expansion Rate</td>
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<td>N.S.</td>
<td>*</td>
<td>N.S.</td>
</tr>
<tr>
<td>Tau</td>
<td>1</td>
<td>*</td>
<td>N.S.</td>
<td>*</td>
</tr>
<tr>
<td>Linear Combination</td>
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<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Margin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* indicates significant effect; N.S. indicates non-significant effects; (Stanard, Flach, Smith, and Warren, 2004 Unpublished)
Table 2.

*Overall design*

<table>
<thead>
<tr>
<th># of Participants</th>
<th># of trials</th>
<th>Display</th>
<th># of trials</th>
<th>Display</th>
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<td>Control</td>
<td>250</td>
<td>Control</td>
</tr>
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<td>250</td>
<td>Control</td>
<td>250</td>
<td>Lowered</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>Control</td>
<td>250</td>
<td>Raised</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>Control</td>
<td>250</td>
<td>No Texture</td>
</tr>
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</table>
Table 3.

Optical R squared, intercept, slope, and strategy classification for release of the accelerator.

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<thead>
<tr>
<th>Sub #</th>
<th>Condition</th>
<th>R²</th>
<th>Slope</th>
<th>Intercept</th>
<th>Classification</th>
<th>R²</th>
<th>Slope</th>
<th>Intercept</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.477</td>
<td>-0.104*</td>
<td>Linear</td>
<td>1</td>
<td>No Change</td>
<td>0.903</td>
<td>Tau</td>
</tr>
<tr>
<td>2</td>
<td>No Change</td>
<td>0.930</td>
<td>0.195</td>
<td>-0.005</td>
<td>Tau</td>
<td>2</td>
<td>No Change</td>
<td>0.935</td>
<td>-0.123**</td>
</tr>
<tr>
<td>3</td>
<td>No Change</td>
<td>0.958</td>
<td>0.293</td>
<td>0.006</td>
<td>Tau</td>
<td>3</td>
<td>No Change</td>
<td>0.979</td>
<td>-0.046**</td>
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<tr>
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</tr>
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<td>Lowered</td>
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<td>Raised</td>
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<td>-0.013</td>
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<td>16</td>
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<td>0.846</td>
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</table>

(* indicates significance of p<.05, ** indicates p<.01)
Table 4.

Optical R squared, intercept, slope, and strategy classification for initiation of braking.

<table>
<thead>
<tr>
<th>Sub #</th>
<th>Condition</th>
<th>R²</th>
<th>Slope</th>
<th>Intercept</th>
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<th>Sub #</th>
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<th>R²</th>
<th>Slope</th>
<th>Intercept</th>
<th>Classification</th>
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<tr>
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<tr>
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<td>-0.374*</td>
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<td>0.692</td>
<td>-0.189**</td>
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<td>0.218</td>
<td>0.055</td>
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(* indicates significance of p<.05, ** indicates p<.01)
Table 5.

Proportions of participants’ optical strategies for the learning and transfer phases.

<table>
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<tr>
<th></th>
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<th>Transfer</th>
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<td>Tau</td>
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<td>75%</td>
</tr>
<tr>
<td>Brake</td>
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<tr>
<td>Percentage</td>
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<td>69%</td>
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